ARIZONA DEPARTMENT OF WATER RESOURCES
FLOOD MITIGATION SECTION

DRAFT

State Standard For Hydrologic Modeling Guidelines

Under the authority outlined in ARS 48-3605(A) the Director of Arizona Department of Water Resources establishes the following standard for Hydrologic Modeling Guidelines in Arizona.

State Standard for Hydrologic Modeling, or "guidelines for the experienced modeler", has been developed to address hydrologic conditions for a variety of statewide watersheds. Include are problems and situations identified by the State Standard Work Group (SSWG) and floodplain managers.

The intended audience is statewide; engineers, professionals and Floodplain Administrators.

The following topics are included:

- Hydrologic Model comparison and recommendation
- Guidelines and parameters
- Model application for specific situations, and associated hydrologic parameters
- Precipitation values (NOAA 14)
- Storm duration
- Unique conditions, such as wildfire burn, overgrazing, logging, drought, rapid snowmelt, urbanization.

The State Standard includes examples addressing the above key issues.

This requirement is effective _________, 2007.

Copies of this State Standard and the State Standard Technical Supplement can be obtained by contacting the Department's Water Engineering Section at (602) 771-8652.

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1.0 INTRODUCTION

1.1 Purpose and Background

This standard was developed under the authority outlined in ARS-48-3605(A) which requires the Director of the Arizona Department of Water Resources to develop and adopt criteria for establishing the 100-year flood and delineating floodplains. The purpose of this document is to provide technical guidance for hydrologic modeling of watersheds in Arizona. This type of modeling is typically used as the basis for performing hydraulic modeling to determine the depth and extent of flooding for the watercourse receiving flow from the watershed. Modeling procedures and techniques can greatly affect the amount of flow estimated to occur in a watercourse for a given storm event. This Standard was prepared to help identify proper modeling practices and should be utilized for hydrologic modeling for floodplain management purposes in Arizona. The goal of the technical guidance is to provide a practical method of producing accurate and reproducible flood discharge estimates. The accuracy of the hydrologic modeling guidelines is a measure of how well the methodology and results of the procedure reproduce the physical process being simulated. Although accuracy is highly desired, it is theoretically impossible to achieve in hydrologic modeling. However, relative accuracy of model results can be evaluated quantitatively through testing and verification against recorded data. Also, relative accuracy of methods for estimating individual model elements (i.e. rainfall, rainfall losses, runoff translation, etc.) can be evaluated qualitatively through an understanding of the theory and limitations of the methodologies. Practicality is a measure of the "best" and most appropriate level of technology to apply. The practicality of a guideline is both a quantitative and a qualitative measure developed through an understanding of the goal of the guideline as well as the theory and limitations of the methodology. Reproducibility is a measure of the degree of interpretation required to implement a guideline. Reproducibility is generally achieved through clear and concise procedures.

Preparation of this Standard was carried out in three phases. Phase I consisted of a comprehensive literature search, data collection, and review. Phase II of the study consisted of review and evaluation of publications related to hydrologic modeling, review of various computer programs for hydrologic modeling, and test watersheds. Phase III involved development of this Standard.

This standard was developed under the auspices of the Arizona Department of Water Resources, State Standards Workgroup. The SSWG is a volunteer group of floodplain management officials from around the state working in conjunction with ADWR to make floodplain management throughout Arizona more uniform and efficient. Everyone in Arizona benefits from these standards.

1.2 General

Selection of rainfall-runoff guidelines that can describe the range of hydrologic conditions that exist in the State of Arizona is a significant undertaking. Initial review of the literature collected in Phase I suggests a number of different methodologies appropriate for use in Arizona. However, the literature does not provide conclusive evidence that any single method is superior in regard to the three benchmarks of accuracy, practicality and reproducibility. Since a detailed evaluation of each methodology is beyond the scope of this State Standard, an initial screening was used to identify methodologies that represent the current state of the practice in Arizona for further evaluation. The current technology being applied in Arizona can be generalized into two categories; the Natural Resource

Conservation Service (NRCS) methodologies and the methodologies set forth in the document titled “Highway Drainage Design Manual – Hydrology”, Arizona Department of Transportation (ADOT), March 1993 (hereafter referred to as ADOT Hydrology Manual or ADOT-HM). These methodologies were evaluated for the three benchmarks and, generally, the recommended State Standard is based on the ADOT Hydrology Manual methods. The details of this screening process and subsequent evaluation may be reviewed in the companion document, “Hydrologic Modeling Guidelines Technical Supplement” (Technical Supplement). References are also included in the Technical Supplement.

2.0 HYDROLOGIC MODELS

2.1 General

There are a number of different mathematical models that are available and capable of simulating hydrologic conditions (rainfall, rainfall losses, runoff transformation). The choice of a hydrologic model should be based on an understanding of the nature of the watershed and the purpose of the study as well as the limitations and computation procedures of the model. At times the model is specified by the regulatory agency, however, often the modeler decides. A model evaluation matrix was developed (Appendix A) to aid the modeler in rainfall-runoff model applicability and selection. With the exception of one model, the hydrologic models evaluated were obtained from FEMA's published list of accepted hydrologic models (*http://www.fema.gov/plan/prevent/fhm/en_hydro.shtm*). Hydrologic models were listed in the matrix and evaluated against 12 categories. The choice of a model should be based on the evaluation criteria listed below for each unique project. Though HEC-1 and HEC-HMS are by far the most common rainfall-runoff models utilized in Arizona, any of the listed models may be utilized given the user understands the limitations and unique characteristics of each model.

2.2 Model Selection

2.2.1 Model Evaluation Criteria

The matrix evaluation categories include the following parameters, which are the analytical considerations for the model selection:

Parameters

This criterion is an indication of the number of modeling methodologies that are available for use. The greater the number of methodologies, the more flexible the model for addressing the unique conditions of Arizona watersheds.

Rainfall methodologies may include historic, synthetic and user-specified distributions.

Losses are the methodologies for interception and infiltration of rainfall.

Runoff Transformation refers to the methodologies for hydrograph development.

Runoff Translation indicates the methodologies for runoff routing.

Diversion is the model's ability to divert runoff between catchments.

Available Unique Parameters include snowmelt, dam breaks, water quality, groundwater and evaporation.

Model Network is the number of elements that can be used to characterize a watershed. Elements include subbasins (rainfall, rainfall losses, unit hydrograph), routing reaches (channel and storage), diversions and combinations.

Urban and Rural Applicability Some models are developed specifically for urban areas.

Other evaluation criteria for model selection include:

> Cost and Availability of the Model This criterion indicates whether the software is available in the public domain and is easily downloaded from the Internet.
>
> Applicability and General Acceptance to Arizona The model is applicable if it utilizes model parameters, which are generally accepted in Arizona. This criterion indicates general acceptance of the model by the Engineering/Floodplain Management community.
>
> The computer Operating Platform is a measure of the degree of difficulty for an average user to input data, execute the model, error check/debug and review/transfer output. A Windows-based, Graphical User Interface (GUI) version is more user-friendly than a dos-based program.
>
> FEMA Acceptance This category indicates whether the model is on the FEMA list of accepted hydrologic models.

2.2.2 Evaluated Models

The evaluated rainfall-runoff models are summarized below:

HEC-1

Developed by Corps of Engineers Hydrologic Engineering Center, HEC-1 is a lumped parameter, single storm event model that simulates surface runoff response of a watershed to precipitation by representing the basin as an interconnected system of hydrologic and hydraulic components (stream channels or reservoirs). Modeling results in hydrographs at points of interest. A variety of methodologies are available to input and model rainfall, losses, runoff transformation and translation and diversion. The Corps no longer supports HEC-1. The last version, 4.1 was released in 1998.

HEC-HMS

HEC-HMS is the successor to HEC-1 and is a “work-in-progress”, as not all of the original functions are available. Many of the original HEC-1 algorithms have been updated and combined with new algorithms. HEC-HMS is a windows based program. In previous versions, data input/output could be somewhat cumbersome. Significant improvements to the interface have been made in the current version.

TR20

Technical Release 20 TR20, like HEC-1 is a lumped parameter, single storm event model developed by the Soil Conservation Service (SCS), forerunner of the Natural Resources Conservation Service (NRCS). The program is a physically based event model, which computes direct runoff resulting from synthetic or actual rain events. The program uses procedures described in the SCS National Engineering Handbook, Section 4, Hydrology. This DOS program is currently out of print and is not supported by the NRCS.

WINTR-20

WINTR-20 is the windows version of TR20. Several aspects of the computational procedure for estimating rainfall excess have been revised to address some of the procedural and theoretical concerns associated with the methodology. It should be noted that these changes in the methodology have not been incorporated into HEC-HMS and perhaps other programs that include the NRCS Curve Number methodology.

TR55

TR55 is a DOS program developed by the United States Department of Agriculture (USDA) using SCS methodology. Unit hydrographs are used to convert rainfall excess into runoff. TR55 is applicable to small watersheds, especially urban. TR55 is based on Technical Release 55, and incorporates SCS procedures, including procedures for calculating travel times of sheet flow, modifications to peak discharge methodology and storage routing procedure. TR55 utilizes four SCS 24-hour synthetic rainfall distributions. TR55 is no longer supported by the NRCS.

WIN TR-55

WIN TR-55 is the windows version of TR-55. WINTR-20 is the driving engine for hydrograph and routing procedures.

SWMM

The Storm Water Management Model (SWMM) was developed for EPA as a single-event model for the analysis of combined sewer overflows. Version 4.4h (current as of October 2005) performs both continuous and single-event simulation. SWMM is a physically based, discrete-time model, which can simulate stormwater quantity and quality. SWMM can utilize a variety of loss and runoff translation methods, applicable to Arizona. SWMM can account for evaporation of standing surface water, snow accumulation and melting, percolation and storage.

SWMM 5

SWMM 5 is the Graphical User Interface (GUI) version of SWMM.

SWMM-XP

SWMM-XP is a proprietary GUI version of SWMM developed by XP Software. This version of SWMM includes a GIS interface.

MIKE 11

MIKE 11 is a proprietary windows-based software package developed by DHI software (Denmark) for the simulation of flow, water quality and sediment transport in rivers, channels and reservoirs. MIKE 11 consists of a core module (HD) and numerous add-on modules. The rainfall-runoff module (RR) contains a number of methods, which can be utilized to estimate runoff. Mike 11 is able to model a complex watershed network, including unique parameters such as snow storage. The price of an unlimited structure and point HD and RR is approximately $18,000, plus an annual software maintenance agreement is required.

Penn State Model

The Penn State Urban Runoff Model (PSURM) was originally developed at Penn State University in cooperation with the City of Philadelphia for combined sewers. PSURM uses curve number methodology and nonlinear reservoir routing with a user-defined lag time. Resultant watershed response time makes PSURM a useful watershed master-planning tool. The original DOS-based program is now available in a window-based version and is obtained by attending a seminar at Penn State.

Pond Pack v.8

The program is for analyzing watershed networks and aiding in sizing detention or retention ponds. Only the NRCS Unit Hydrograph method and NRCS time of time of concentration formulas approved by State agencies in charge of flood control or floodplain management are acceptable for use within the subject State. Pond Pack can handle an unlimited number of synthetic or real storm events of any duration or distribution.

DRM3

DR3M is a watershed model for routing storm runoff through a branched system of pipes and/or natural channels using rainfall as input. DR3M provides detailed simulation of storm-runoff periods selected by the user. There is daily soil-moisture accounting between storms. A drainage basin is represented as a set of overland-flow, channel, and reservoir segments, which jointly describe the drainage features of the basin. This model is usually used to simulate small urban basins. Interflow and base flow are not simulated. Snow accumulation and snowmelt are not simulated. This is a continuous event model. Calibration to actual flood events is required.

HSPF 10.10

HSPF simulates for extended periods of time the hydrologic, and associated water quality, processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. HSPF uses continuous rainfall and other meteorologic records to compute streamflow hydrographs and pollutographs. HSPF simulates interception soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton. The program can simulate one or many pervious or impervious unit areas discharging to one or many river reaches or reservoirs. Frequency-duration analysis can be done for any time series. Any time step from 1 minute to 1 day that divides equally into 1 day can be used. Any period from a few minutes to hundreds of years may be simulated. HSPF is generally used to assess the effects of land-use change, reservoir operations, point or non-point source treatment alternatives, flow diversions, etc. Programs, available separately, support data preprocessing and post processing for statistical and graphical analysis of data saved to the Watershed Data Management (WDM) file. This is a continuous event model. Calibration to actual flood events is required.

PRMS

PRMS is a modular-design, deterministic, distributed-parameter modeling system developed to evaluate the impacts of various combinations of precipitation, climate, and land use on streamflow, sediment yields, and general basin hydrology. Basin response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water-balance relationships, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields, and ground-water recharge. Parameter-optimization and sensitivity analysis capabilities are provided to fit selected model parameters and evaluate their individual and joint effects on model output. The modular design provides a flexible framework for continued model-system enhancement and hydrologic-modeling research and development. This is a continuous event model. Calibration to actual flood events is required.

3.0 MODELING PROCESS AND PROCEDURES

3.1 General

The following methodologies and procedures for hydrologic model development were prepared using the criteria and parameter recommendations documented in the Technical Supplement. In general, recommended methodologies and procedures presented herein are consistent or identical as those presented in the ADOT Hydrology Manual. As such, much of the methodology discussion and procedures for parameter estimation are taken directly from the ADOT Hydrology Manual. Where additional data, procedures and/or information are provided, effort was made to properly document the source and provide appropriate references.

Although this state standard attachment does not make a specific hydrologic model recommendation, it is recognized that the majority of modeling is being accomplished using HEC-1 and HEC-HMS. To facilitate discussion of the methods and procedures presented herein, references are made to HEC-1 routines or specific variables. In addition, an example input file is included at the end of this section (Figure 12). References are made to the example input file in the following discussion to illustrate development of the HEC-1 file. It is assumed in the discussion below that the reader has access to the HEC-1 Users Manual for reference regarding specific input requirements. For purposes of the following discussion the term “record” refers to a line of input in the HEC-1 file. Each “record” starts with a two character descriptive, which tells the program what kind of data is on that record. The term “field” refers to a set of 8 characters within a given record. There are up to 10 “fields” within each “record.” Please note that field 1 of any record only consists of 6 characters because the 2 character record identifier occupies the first two characters of any record.

3.2 Project Description and Initialization

Each HEC-1 model can (and should) be started with one or more ID records which provide information about the name, location, date, file name, modeler, storm event and other pertinent information about the model (see example input file).

The next record is the IT record. The input-output time interval (NMIN) for the HEC-1 model is specified, in minutes, on field 1 of the IT record (see example input file). Selection of NMIN corresponds to the Time of Concentration (T_c). As a general rule, NMIN = 0.15 T_c but can range between $0.1T_c$ and $0.25T_c$. Specify the number of ordinates (NQ) (maximum of 2,000) in field 4 of the IT record. The simulation duration is the product of the time interval and the number of ordinates (e.g., 5 minutes times 300 ordinates is 1500 minutes, or 25 hours).

The level of output detail can be specified on the IO record that follows the IT line (see example input file). A value of 1 in field 1 (IPRT) provides the most detailed output, a value of 5 provides the least output.

For most rainfall-runoff simulations, the remainder of the HEC-1 file consists of groups or records representing discrete components of the model including;

- Subbasin Runoff
- Channel Routing
- Storage Routing
- Hydrograph Combinations
- Diversions

Each model component is identified by a KK record (hydrograph computation identification). Field 1 of the KK record is used as a unique identifier which will appear in the output for this model component. The KK record may be followed by optional (but highly recommended) KM record(s). The KM record(s) can be used to provide a description (in fields 2 through 10) of what the component reflects (subbasin runoff, routing, diversion, etc.). The reader is directed to the example input file to review the file structure and note that the beginning of each component includes a KK and KM record. There is no limit to the number of KM records. The reader will note that each component in the example file is separated by a record with an "*". This is an acceptable formatting technique which is helpful in separating discrete components of the model. It was done in the example input file included herein only to help identify each component and is not a required modeling record.

3.3 Precipitation Data

3.3.1 General

It is generally accepted that for larger watersheds in Arizona, the major flood producing storms generally occur in the winter months due to frontal or convergence activity. A frontal or convergence storm, herein referred to as a general storm, produces large volumes of relatively low intensity rainfall over long durations. General storms are also typically large in areal extent.

For smaller watersheds, the major flood producing storms generally occur in the summer months due to convective activity. A convective storm, herein referred to as a local storm, produces high intensity rainfalls over relatively short durations and small areal extent. Occasionally, these storms can also be imbedded in general summer storms that are typically a result of tropical storms that move into the state from the Pacific Ocean.

For design hydrology, the characteristics of the major flood producing storms are simulated using a synthetic storm. Criteria for synthetic storms can be developed from long-term data or from a historic storm. Components of a synthetic storm are basin average rainfall depth and temporal distribution.

3.3.2 Depth - Duration - Frequency Statistics

Rainfall depth should be selected using the National Atmospheric and Oceanic Administration (NOAA) Atlas 14 precipitation values. These values can be obtained using NOAA's Hydrometeorological Design Studies Center – Precipitation Frequency Data Server web site found at http://hdsc.nws.noaa.gov/hdsc/pfds/sa/az_pfds.html. At this web site, point rainfall values can be found by entering the latitude and longitude of the watershed of interest. Typically, the centroid of the watershed is used as the point of interest for rainfall depth. However, it may be necessary to select multiple points of interest to reflect orographic effects. Precipitation frequency estimates are provided for return intervals ranging from 2- to 500-years and for durations ranging from 5 minutes to 60 days. The mean precipitation estimates should be used (i.e., not the upper or lower 90% confidence interval estimates).

Storm duration is a function of watershed T_c. This allows for all portions of the watershed to contribute runoff at the basin outlet. Storm durations for most conditions will either be 3-, 6- or 24-hours. Other storm durations can be used, but will require careful selection of appropriate depth-area reduction factors.

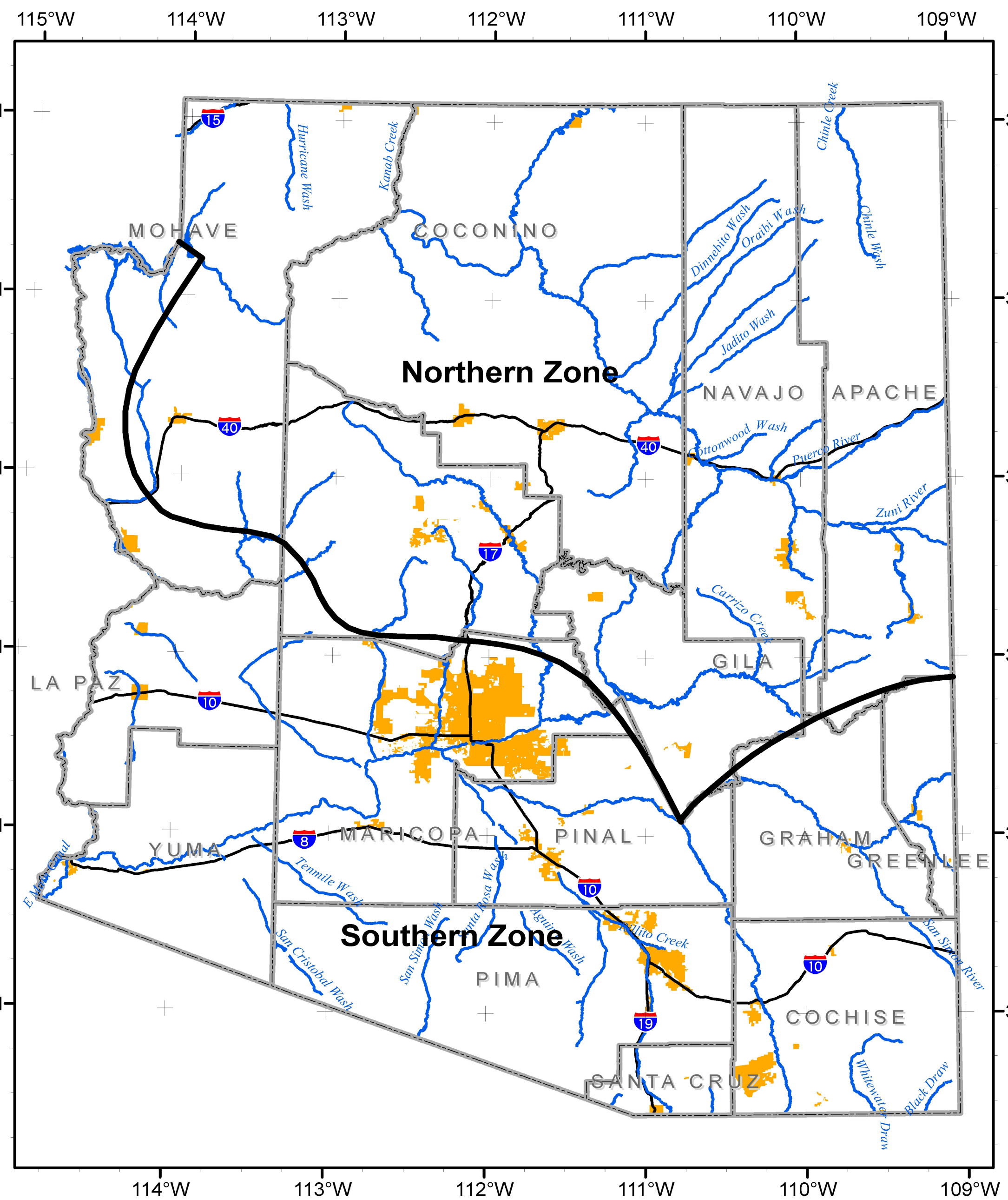
3.3.3 Depth – Area Reduction

The rainfall values discussed above are point rainfall values. However, these depths are not the areally averaged rainfall over the watershed in question. A reduction factor is used to convert the point rainfall to an equivalent uniform depth of rainfall over the entire watershed. The reduction factor varies depending on storm duration and watershed location. Two depth-area relations appropriate for use in Arizona are presented in the NOAA Technical Memorandum NWS HYDRO-40. The two relations represent different depth-area zones. The different zones are illustrated in Figure 1. Depth-area reduction factors for each zone are listed in Table 3.0 and present graphically in Figures 2 and 3.The reduction factor (read from the vertical axis) is used as a multiplier for the point precipitation value of interest (e.g., if rainfall = 3.00 inches and reduction factor = 0.8, then areally-reduced rainfall 3.00 x 0.80 = 2.40 inches). The resulting rainfall value (in inches) and the total watershed area being modeled (in square miles) are entered on fields 1 and 2, respectively, of the JD record (see example input file).

Table 3.0
Depth-Area Reduction Factors

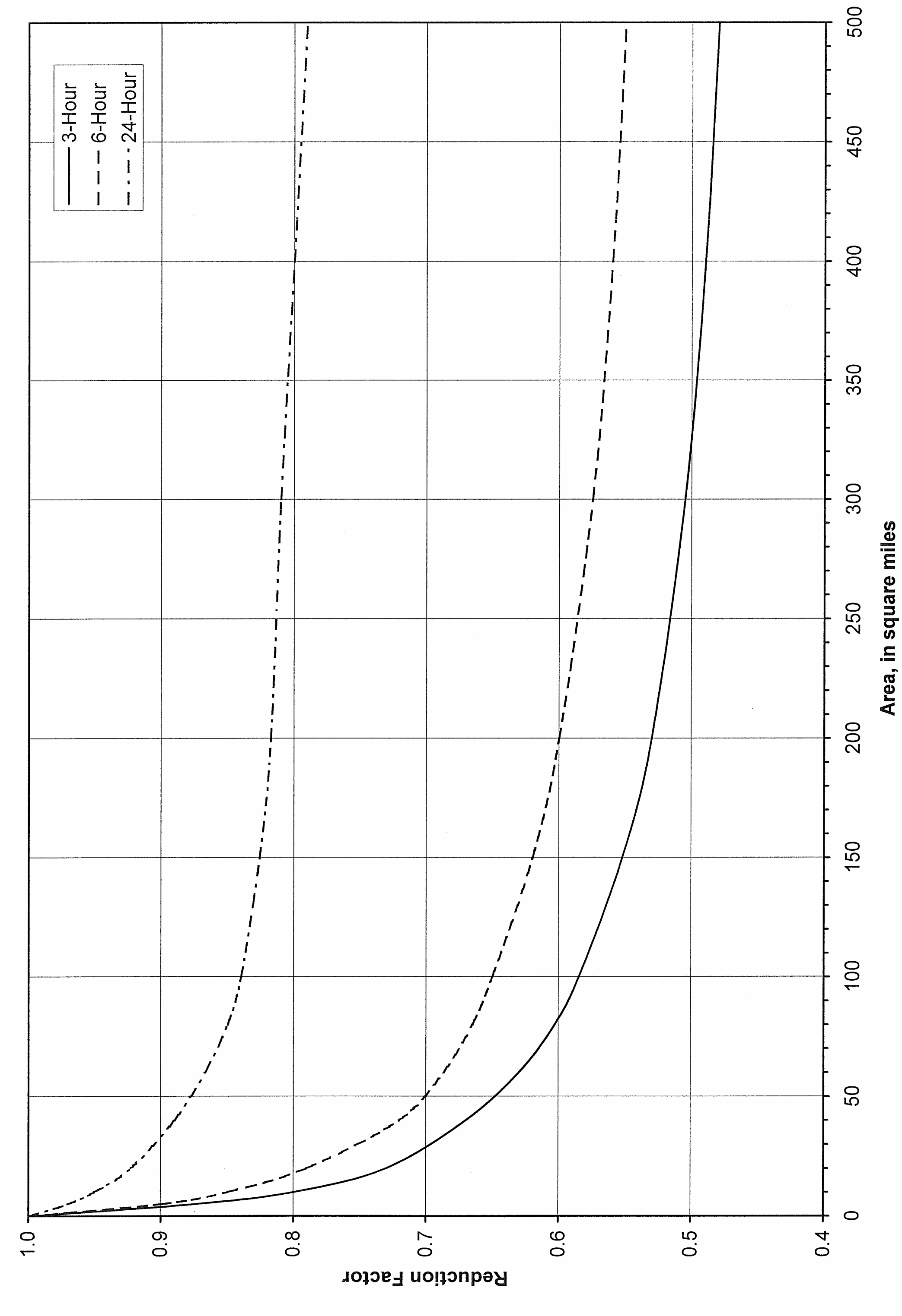
Area	3-hour		6-hour		24-hour	
(sq.miles)	Northern	Southern	Northern	Southern	Northern	Southern
0	1.000	1.000	1.000	1.000	1.000	1.000
5	0.875	0.860	0.900	0.860	0.970	0.930
10	0.800	0.800	0.850	0.800	0.950	0.890
20	0.730	0.740	0.790	0.740	0.923	0.850
40	0.670	0.680	0.720	0.680	0.890	0.795
60	0.630	0.638	0.687	0.645	0.867	0.760
80	0.603	0.610	0.665	0.620	0.850	0.734
100	0.585	0.590	0.650	0.600	0.840	0.715
150	0.552	0.560	0.620	0.574	0.826	0.690
200	0.530	0.540	0.600	0.555	0.818	0.670
300	0.505	0.515	0.575	0.530	0.810	0.650
400	0.490	0.495	0.560	0.515	0.800	0.640
500	0.480	0.480	0.550	0.510	0.790	0.630

FIGURE 3.1
DEPTH-AREA RELATION ZONES



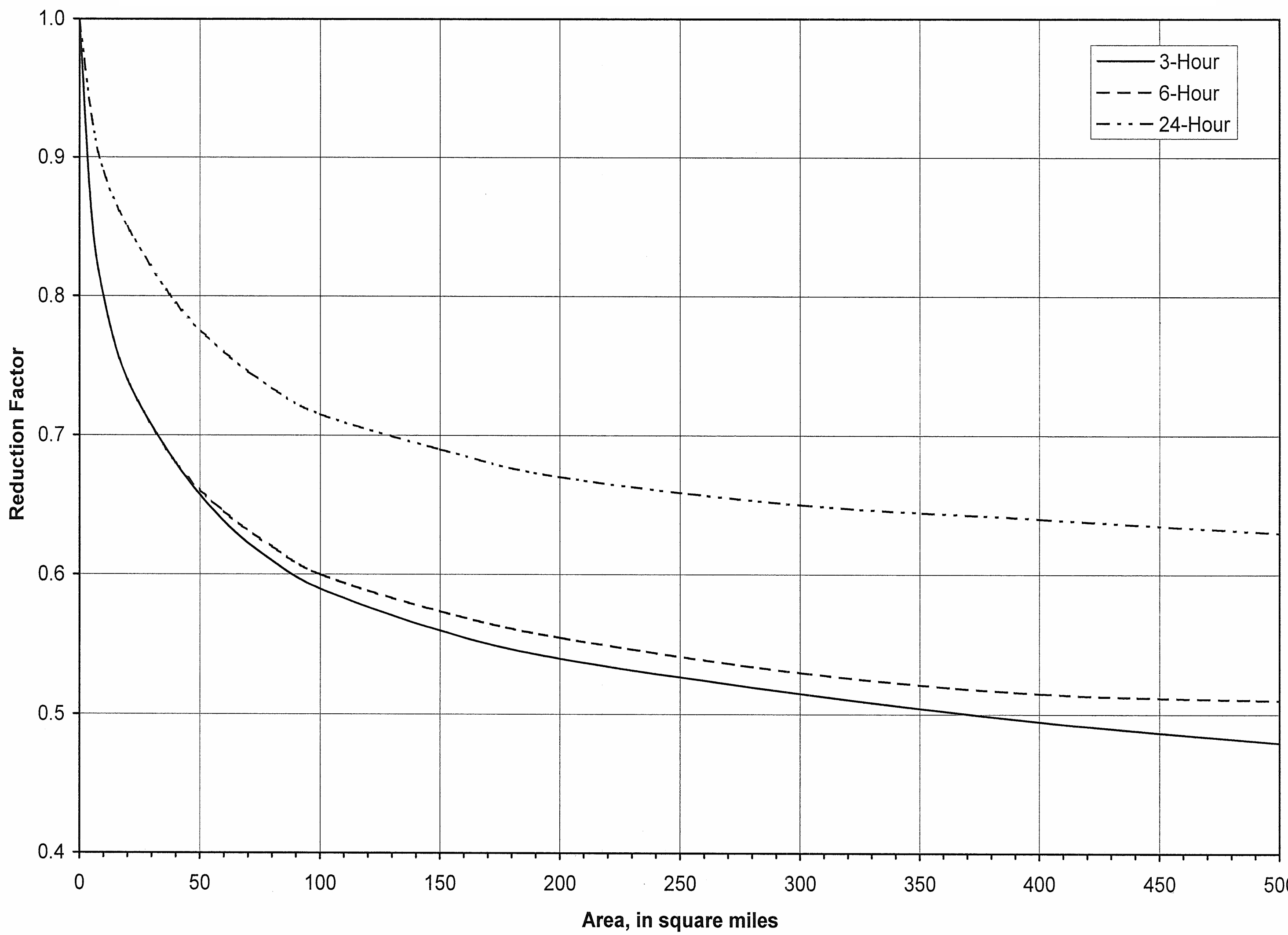
Adapted from Figure 13, NWS HYDRO-40

FIGURE 3.2
DEPTH-AREA REDUCTION RELATION FOR NORTHERN ARIZONA



Adapted from Figure 15, NWS HYDRO 40

FIGURE 3.3
DEPTH-AREA REDUCTION RELATION FOR SOUTHERN ARIZONA



Adapted from Figure 14, NWS HYDRO 40

3.3.4 Rainfall Distribution

Unadjusted point rainfall for the watershed is distributed temporarily using a symmetrically nested distribution, referred to as the hypothetical distribution. Information about the hypothetical distribution is available in the U.S. Army Corps of Engineers, Training Document No. 15 (1982). When using HEC-1, rainfall depths for specific intra-storm durations are input on the PH record up to the desired storm duration.

3.3.5 Procedures

1. Determine the latitude and longitude coordinates (in decimal degrees) at the centroid of the watershed (note that longitude for the western hemisphere is input as a negative number).

   If multiple points of interest are desired or if orographic effects make selection of a single set of rainfall statistics inappropriate, determine the latitude and longitude of each desired location.

2. Input the coordinates in the appropriate fields of the NOAA Precipitation Data Server, see Figure 4, and submit the data (Note: use partial duration series).

3. From the resulting table, see Figure 5, input the rainfall depth data on the PH record. (Note: only the mean data should be used (unless the local jurisdiction requires using the upper 90% confidence limits on smaller watersheds).

   a. Field 1: PFREQ

      If the analysis is for a flood frequency of 2-, 5- or 10-year, input the following:

Flood Frequency	PFREQ
2-year	50
5-year	20
10-year	10

      For all other flood frequencies, PFREQ is left blank.

   b. Field 2: TRSDA

      Leave blank, areal reduction accomplished using the JD record.

   c. Fields 3 through 10: PNHR(i)

      Input the rainfall depths for the intra-storm durations up to the total storm duration per the following:

	Duration	
Field	**Intra-Storm**	**Total Storm**
3	5-min	3-,6- and 24-hour
4	15-min	3-,6- and 24-hour
5	1-hour	3-,6- and 24-hour
6	2-hour	3-,6- and 24-hour
7	3-hour	3-,6- and 24-hour
8	6-hour	6- and 24-hour
9	12-hour	24-hour

10	24-hour	24-hour

If multiple points of interest are desired, areally average each intra-storm duration rainfall depth to input a single set of values.

4. Select the depth-area reduction factor for the total watershed area using either Figure 2 or 3. Multiply the point value for the total storm duration by the depth-area reduction factor. Input the total watershed area and areally reduced rainfall depth on fields 1 and 2, respectively, on the JD record.

FIGURE 3.4
NOAA ATLAS 14 PRECIPITATION FREQUENCY DATA SERVER INPUT

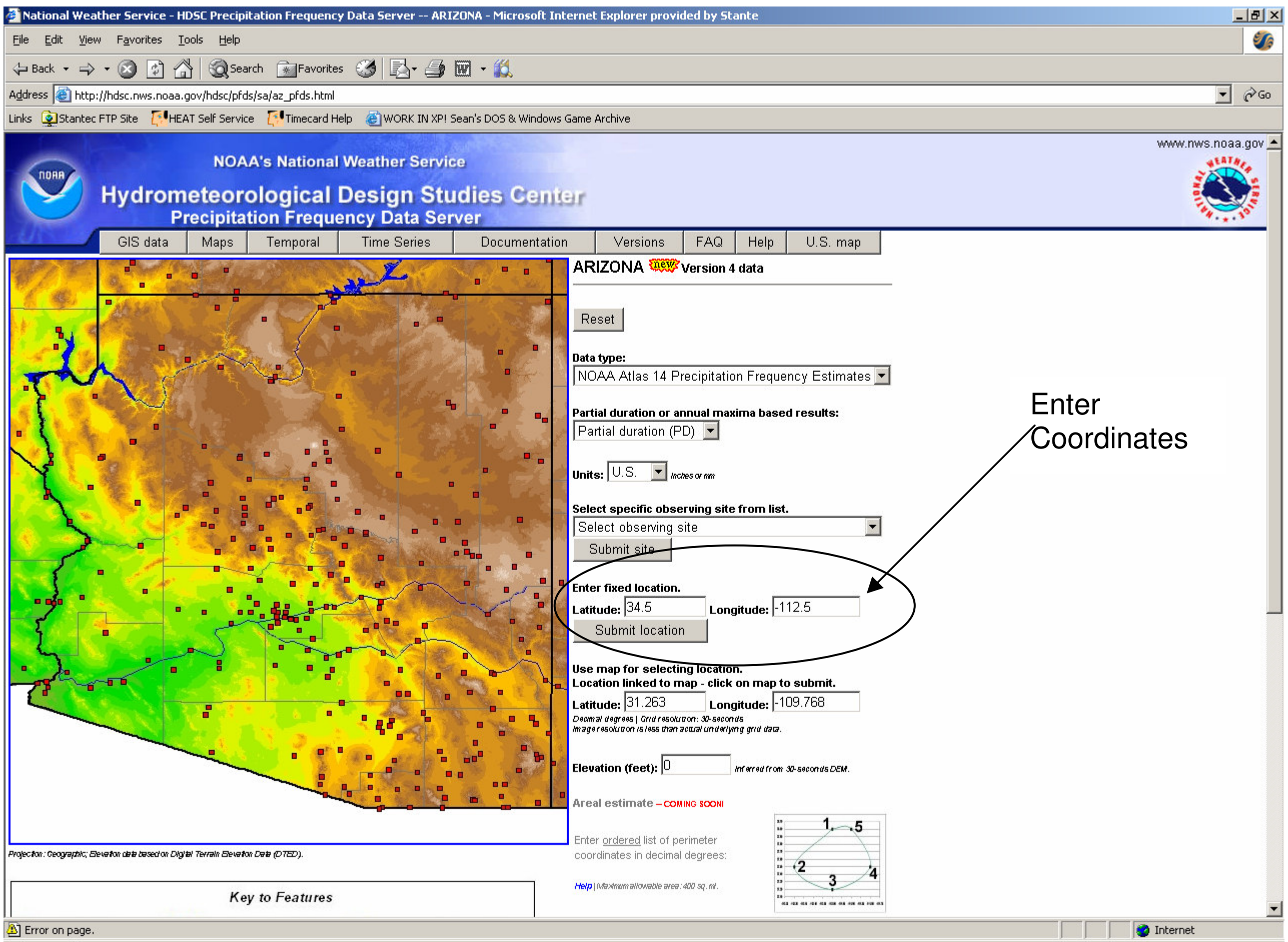
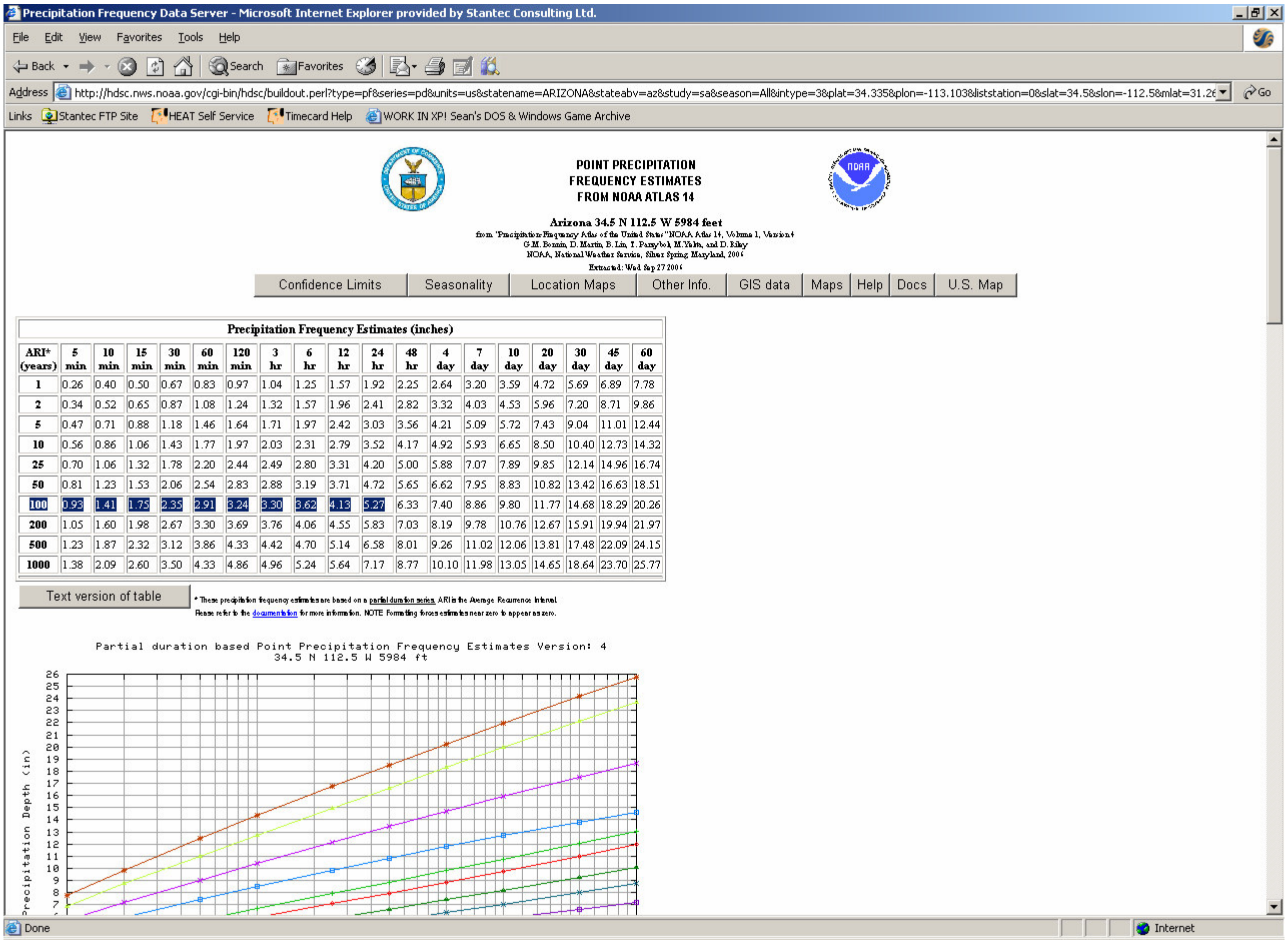


FIGURE 3.5
NOAA ATLAS 14 PRECIPITATION FREQUENCY DATA SERVER OUTPUT



POINT PRECIPITATION
FREQUENCY ESTIMATES
FROM NOAA ATLAS 14

Arizona 34.5 N 112.5 W 5984 feet

Extracted: Wed Sep 27 2006

Confidence Limits | Seasonality | Location Maps | Other Info. | GIS data | Maps | Help | Docs | U.S. Map

Precipitation Frequency Estimates (inches)

ARI* (years)	5 min	10 min	15 min	30 min	60 min	120 min	3 hr	6 hr	12 hr	24 hr	48 hr	4 day	7 day	10 day	20 day	30 day	45 day	60 day
1	0.26	0.40	0.50	0.67	0.83	0.97	1.04	1.25	1.57	1.92	2.25	2.64	3.20	3.59	4.72	5.69	6.89	7.78
2	0.34	0.52	0.65	0.87	1.08	1.24	1.32	1.57	1.96	2.41	2.82	3.32	4.03	4.53	5.96	7.20	8.71	9.86
5	0.47	0.71	0.88	1.18	1.46	1.64	1.71	1.97	2.42	3.03	3.56	4.21	5.09	5.72	7.43	9.04	11.01	12.44
10	0.56	0.86	1.06	1.43	1.77	1.97	2.03	2.31	2.79	3.52	4.17	4.92	5.93	6.65	8.50	10.40	12.73	14.32
25	0.70	1.06	1.32	1.78	2.20	2.44	2.49	2.80	3.31	4.20	5.00	5.88	7.07	7.89	9.85	12.14	14.96	16.74
50	0.81	1.23	1.53	2.06	2.54	2.83	2.88	3.19	3.71	4.72	5.65	6.62	7.95	8.83	10.82	13.42	16.63	18.51
100	0.93	1.41	1.75	2.35	2.91	3.24	3.30	3.62	4.13	5.27	6.33	7.40	8.86	9.80	11.77	14.68	18.29	20.26
200	1.05	1.60	1.98	2.67	3.30	3.69	3.76	4.06	4.55	5.83	7.03	8.19	9.78	10.76	12.67	15.91	19.94	21.97
500	1.23	1.87	2.32	3.12	3.86	4.33	4.42	4.70	5.14	6.58	8.01	9.26	11.02	12.06	13.81	17.48	22.09	24.15
1000	1.38	2.09	2.60	3.50	4.33	4.86	4.96	5.24	5.64	7.17	8.77	10.10	11.98	13.05	14.65	18.64	23.70	25.77

Text version of table

* These precipitation frequency estimates are based on a partial duration series. ARI is the Average Recurrence Interval. Please refer to the documentation for more information. NOTE: Formatting forces estimates near zero to appear as zero.

Partial duration based Point Precipitation Frequency Estimates Version: 4
34.5 N 112.5 W 5984 ft

3.4 Subbasin Data

3.4.1 Prepare Watershed Map

Obtain USGS 7.5 minute quadrangles (or higher resolution/scale topographic mapping if available) for the watershed area of interest. USGS quadrangles are available in paper and digital format from the USGS and many local engineering, drafting and recreation firms. Where possible or necessary, utilize aerial photography and field investigations to verify watershed boundaries.

When distributary flow conditions are encountered during watershed delineation, the delineation should be done so as to include all possible contributing areas (i.e., if a stream can drain either away or into the drainage area of interest, it should be assumed to drain into the area of interest).

Delineate the entire watershed concentrating at the point of interest. If there is more than one point of interest, delineate the watershed concentrating at each point of interest. Then, break the overall watershed into subbasins, if necessary. The breakdown of the overall watershed into subbasins should be guided by the following criteria:

- The subbasin sizes should be as uniform as possible,
- Subbasins should have fairly homogeneous land-use and geographic characteristics. For example, mountain, hillslope and valley areas should be separated by subbasin where possible.
- Soils and vegetation characteristics should be fairly homogenous.
- Subbasins should be delineated for each tributary at the confluence of major stream branches within the watershed, where applicable.

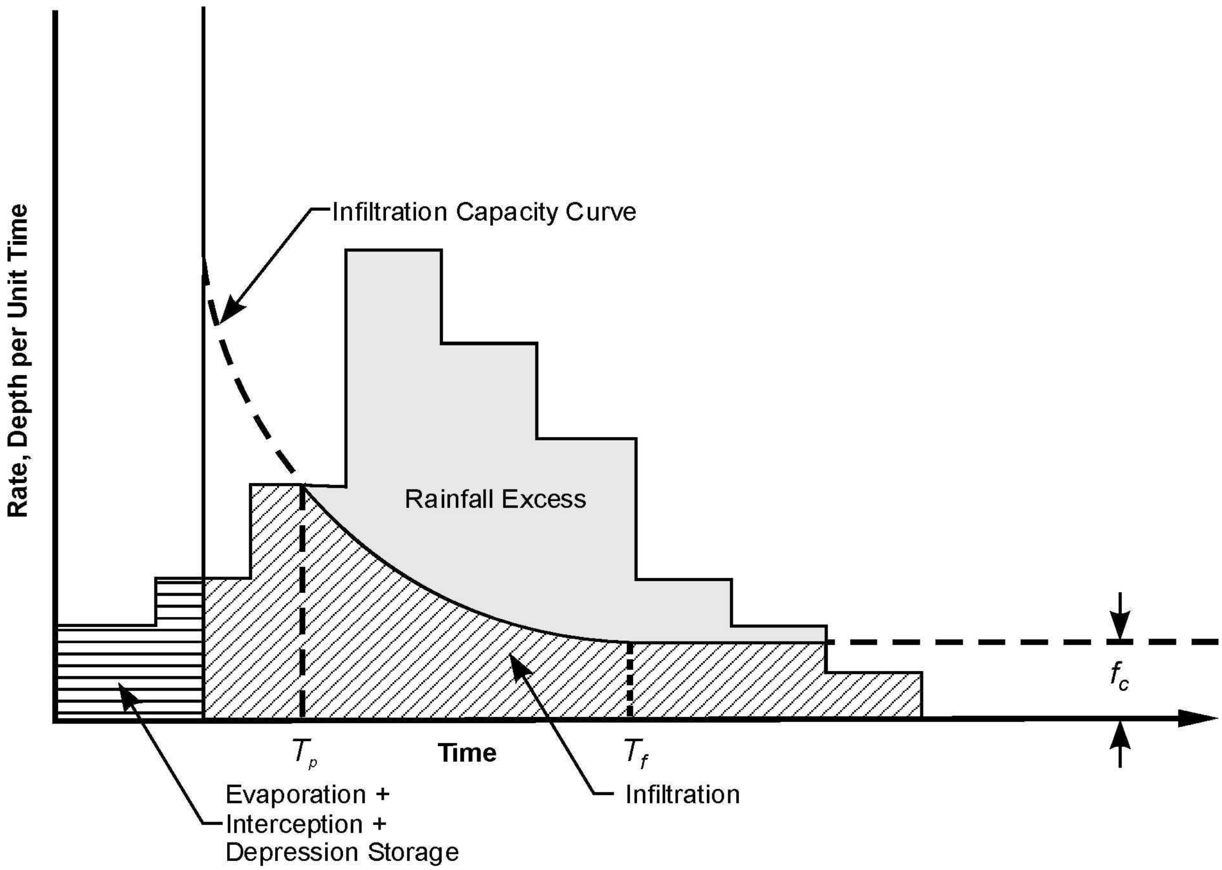
The size of each subbasin in the watershed should be measured in square miles and is entered on the BA record in the HEC-1 model for each subbasin (see example input file, Figure 12 at the end of this section).

3.4.2 Rainfall Losses

Rainfall losses are generally considered to be the result of evaporation of water from the land surface, interception of rainfall by vegetal cover, depression storage on the land surface and the infiltration of water into the soil matrix. The magnitude of rainfall losses is typically expressed as an equivalent uniform depth, in inches. By a mass balance, rainfall minus rainfall loses equals rainfall excess. Estimation of rainfall loses is an important element in flood analyses that must be clearly understood and estimated with care.

For the duration of a rainfall event, there are three phases of rainfall loss processes. These phases are illustrated in Figure 6. In the first phase, rainfall losses are a function of the depression storage, interception, evaporation and infiltration capacity of the soil. During this phase, no runoff excess is produced. The accumulated rainfall loss during this phase is called the Initial Abstraction, I_a. Note, that the losses during this phase are the summation of all mechanisms including infiltration. The magnitude of I_a is difficult to estimate. However, for the purposes of conducting flood analyses, reasonable values can be estimated by looking at each mechanism independently.

FIGURE 3.6
SIMPLIFIED REPRESENTATION
OF RAINFALL LOSSES
(Adapted from Flood Control District of Maricopa County Drainage Design Manual, Volume I, Hydrology)



Evaporation and Interception

From a practical standpoint, the magnitude of rainfall loss due to evaporation that can occur during a storm event capable of producing flooding is negligible and should be assumed to be zero. Losses due to interception are a function of vegetation type, maturity and canopy cover. Values for interception for select vegetation types are listed in Table 3.1 In addition to the values listed in Table 3.1, Thompson (1986) found that interception losses for the Mesquite plains of Texas are less than most deciduous forests. The lower losses were attributed to the less dense canopy cover of the Mesquite plains and the smaller leaf size of Mesquite compared to typical deciduous forest conditions. This would suggest that for many vegetative types/zones common to Arizona (pinyon, Juniper, Sonora Desert Species, etc.) that interception losses are less than 0.09. In general, it can be assumed that except for agricultural areas, the contribution of interception to the overall magnitude of I_a is minimal.

Table 3.1
Interception for Select Vegetation Types
Adapted from Flood-Runoff Analysis (USACE, 1994)

Vegetation Type	Interception (inches)
Forest(Coniferous/Deciduous)	0.09
Cotton	0.33
Alfalfa	0.11
Grassland/Meadow Grass	0.08

Depression Storage

Losses due to depression storage, also referred to as surface retention, is a function of the physiography and land use of an area. Examples of features that result in surface retention are puddles, roadway gutters and swales, roofs, irrigation bordered fields and lawns, walls, etc. Estimates of surface retention for various physiographic and land use conditions are provided in Table 3.2.

Table 3.2
Estimates of Depression Storage

Feature Type	Depression Storage (inches)	Source
Impervious Surface	0.0625 – 0.125	Tholin and Keefer (1960)
Turf	0.25 – 0.50	Tholin and Keefer (1960)
1% Land Slope	0.11	Viessman (1967)
2.5% Land Slope	0.25	Viessman (1967)
Urban Area in Albuquerque, NM	0.04	Sabol (1983)
Alluvial Plain, Albuquerque, NM	0.10 –0.20	Sabol and Others (1982a)
Pinon – Juniper Hill slopes, Albuquerque, NM	0.09	Sabol and Others (1982b)
Eastern Plans Rangeland, Albuquerque, NM	0.39	Sabol and Others (1982b)
Sand, Intense storm	0.20	Hicks (1944)
Loam, Intense storm	0.15	Hicks (1944)
Clay, Intense Storm	0.10	Hicks (1944)

Infiltration During Initial Abstraction

Infiltration is the rate at which water enters the soil. Infiltration losses are a significant component of I_a and together with surface retention account for the majority of I_a. Infiltration is a function of soil properties, vegetation influences on soil structure, surface cover of rock and vegetation and land use influences such as tillage. Infiltration changes with time. The rate of change is controlled by the antecedent conditions and the ability of the soil matrix to draw in water. Information and data necessary for estimating infiltration rate is discussed later in this section.

The end of the Ia phase occurs at the onset of surface ponding. The Time to Ponding; Tp is effected by antecedent conditions and rainfall intensity. High antecedent conditions (moist soil) and/or high rainfall intensities shorten Tp while low antecedent conditions (dry soil) and/or low rainfall intensities lengthen Tp.

The second rainfall loss phase is primarily a function of infiltration. During this phase, the infiltration rate continues to change with time. The end of this phase (T_f) occurs when the soil and rainfall conditions are such that the infiltration rate reaches a steady-state, equilibrium rate, fc.

For the third and final, phase the only meaningful loss is due to infiltration. During this phase, infiltration is at the steady-state, equilibrium rate of the soil.

Method

The three phases of the rainfall loss process can be simplified into two components. The first component is the summation of all losses other than infiltration (evaporation, interception and surface retention) and is herein referred to as initial losses. Initial losses appropriate for use in Arizona are in listed in Table 3.3.

The second component is infiltration. Infiltration can be estimated using the Green and Ampt infiltration equation. The Green and Ampt infiltration is described by three parameters.

- Hydraulic conductivity at the steady-state rate, XKSAT, expressed in inches per hour
- Average capillary suction in the wetted zone, PSIF, expressed in inches.
- Soil moisture deficit (antecedent conditions), DTHETA, dimensionless

The Green and Amp infiltration equation parameters are estimated as a function of soil texture. There are 12 soil texture classifications according to the U.S. Department of Agriculture classification system. Those classifications along with representative values of the Green and Ampt equation parameters for bare ground conditions are list in Table 3.4. DTHETA for three different states (antecedent conditions) are also listed in Table 3.4.

- Dry – no irrigated lands such as desert, rangeland and forest
- Normal – irrigated lawn, turf and permanent pasture
- Saturate – irrigated agricultural lands

From the values listed in Table 3.4 relations can be derived for XKSTA to PSIF and XKSAT to DTHETA. Those relations are shown graphically in Figure 7.

Table 3.3
Initial Loss for Various Land Surfaces in Arizona
(Source: Table 3-1, ADOT Hydrology Manual)

Land Use and/or Land Cover	**Surface Retention Loss (inches)**
Natural	
Desert and rangeland, flat slope	0.35
Desert and rangeland, hill slope	0.15
Mountain with vegetated surface	0.25
Developed (Residential and Commercial)	
Lawn and turf	0.20
Desert landscape	0.10
Pavement	0.05
Agricultural	
Tilled fields and irrigated pasture	0.50

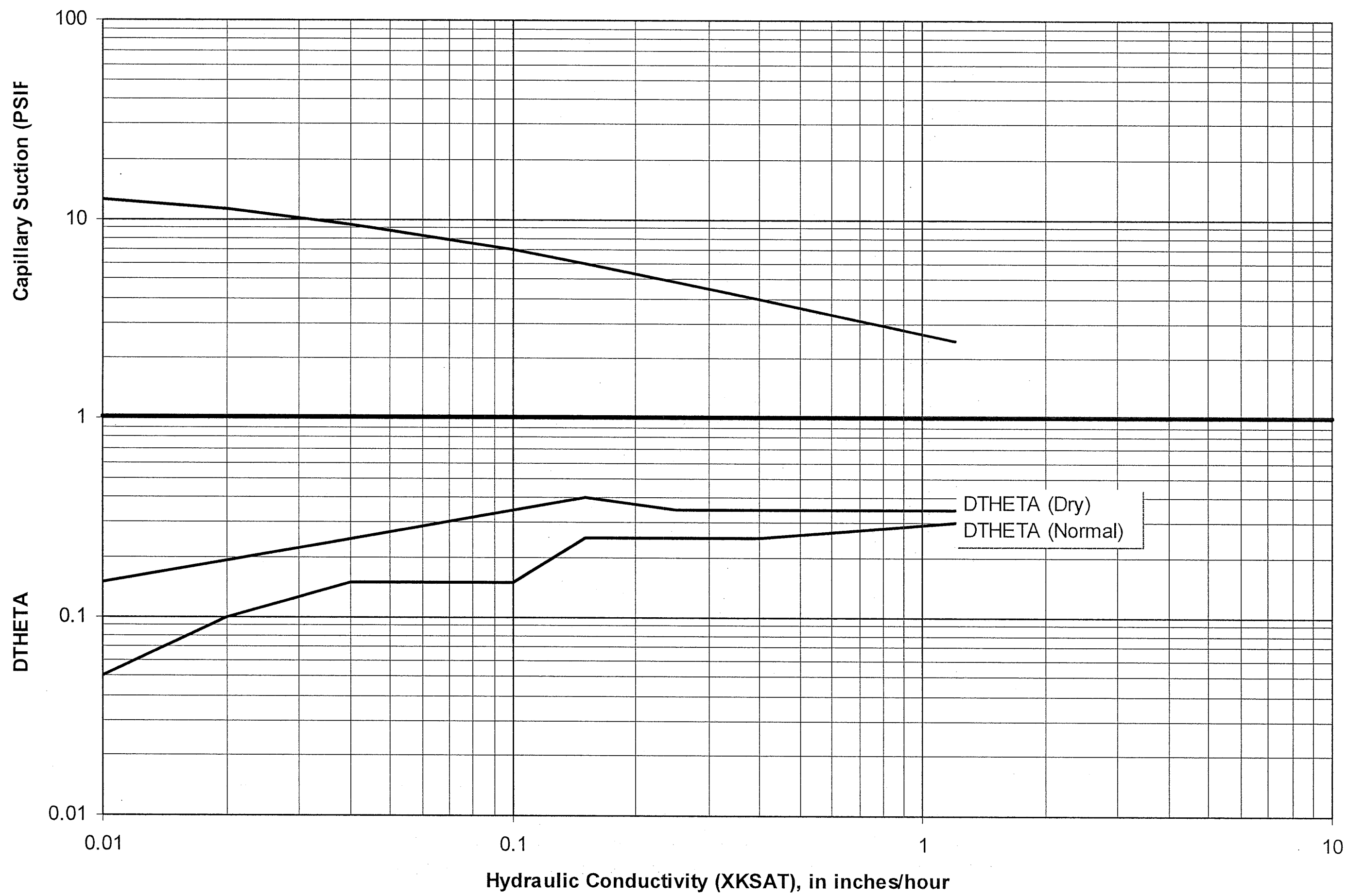
Table 3.4
Green and Ampt Infiltration Equation Loss Rate
Parameter Values for Bare Ground
(Source: ADOT Hydrology Manual)

Soil Texture Classification	DTHETA[a] Dry	Normal	Saturated	XKSAT in/hr	PSIF inches
Sand[b]	.35	.30	0	4.6	1.9
Loamy Sand	.35	.30	0	1.2	2.4
Sandy Loam	.35	.25	0	.40	4.3
Loam	.35	.25	0	.25	3.5
Silt Loam	.40	.25	0	.15	6.6
Silt	.35	.15	0	.10	7.5
Sandy Clay Loam	.25	.15	0	.06	8.6
Clay Loam	.25	.15	0	.04	8.2
Silty Clay Loam	.30	.15	0	.04	10.8
Sandy Clay	.20	.10	0	.02	9.4
Silty Clay	.20	.10	0	.02	11.5
Clay	.15	.05	0	.01	12.4

[a] Selection of DTHETA:
Dry – for non-irrigated lands, such as desert and rangeland
Normal – for irrigated lawn, turf, and permanent pasture
Saturated – for irrigated agricultural lands

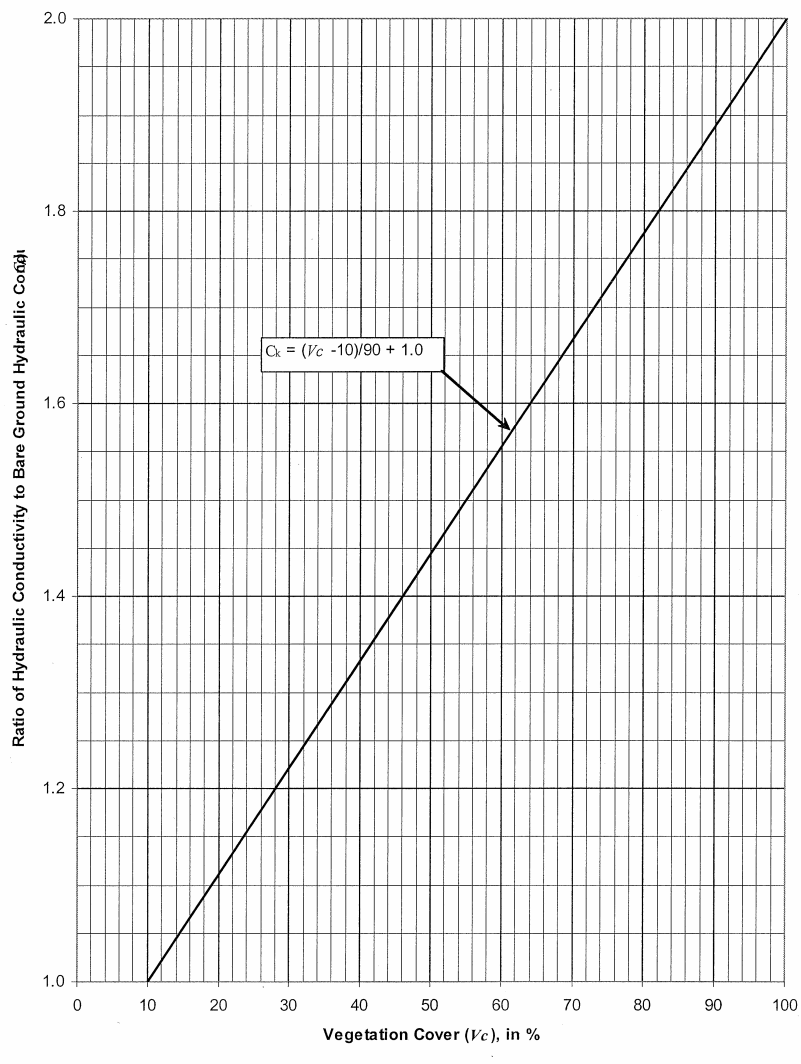
[b] The use of the Green and Ampt Infiltration Equation for drainage areas or subbasins that are predominantly sand should be avoided and the IL+UR method should be used.

FIGURE 3.7
COMPOSITE VALUES OF PSIF
AND DTHETA AS A FUNCTION OF XKSAT
(to be used for area-weighted averaging
of Green and Ampt parameters)



As stated previously, infiltration is effected by vegetation conditions. For the Green and Ampt equation the parameter that is adjusted to account for this is XKSAT. The vegetative condition used to adjust XKSAT is the ground/canopy cover. Adjustment factors for vegetation cover percentages are provided graphically in Figure 8. Adjustment for vegetation cover is made for all soil texture classifications except sand and loamy sand. Adjustment for these soils could result in overestimation of losses due to infiltration.

FIGURE 3.8
EFFECT OF VEGETATION COVER
ON HYDRAULIC CONDUCTIVITY
FOR HYDRAULIC SOIL GROUPS B, C AND D,
AND FOR ALL SOIL TEXTURES
OTHER THAN SAND AND LOAMY SAND



Impervious Area

Although not a rainfall loss component, there is one additional element to consider in the estimation of rainfall excess that that is the impervious areas within the watershed.

Impervious area (or nearly impervious area) is composed of rock outcrop, paved roads, parking lots, rooftops, and so forth. When performing watershed modeling with the HEC-1 program, the impervious area is to be the effective (directly connected to the watershed outlet without flowing over pervious surfaces) impervious area. For urbanized areas, the effective impervious area should be estimated from aerial photographs, if available, site visits and /or guidance as provided in Table 3.5. For areas that are presently undeveloped, but for which flood estimates are desired for future urbanized conditions, estimates of effective impervious area should be obtained based on regional planning and land-use zoning as determined by the local jurisdiction. Estimates of the effective impervious area for urbanizing areas should be selected from local guidance, if available, along with the general guidance that is provided in Table 3.5. For undeveloped areas, the effective impervious area is often 0 percent. However, in some watersheds there could be extensive rock outcrop that would greatly increase the imperviousness of the watershed. Care must be exercised when estimating effective impervious area for rock outcrop. Often the rock outcrop is relatively small (in terms of the total drainage area) and is of isolated units surrounded by soils of relatively high infiltration capacities. Relatively small, isolated rock outcrop should not be considered as effective impervious area because runoff must pass over pervious surfaces before reaching the point of discharge concentration. For watersheds that have significant, contiguous rock outcrop, it may be necessary to establish those areas as subbasins so that the direct runoff can be estimated and then routed (with channel transmission losses, if appropriate) to the point of interest. Paved roads through undeveloped watersheds will not normally contribute to effective impervious area unless the road serves as a conveyance to the watershed outlet.

Table 3.5
General Guidance For Selecting
Effective Impervious Area (RTIMP)

Land Use (1)	Effective Impervious Area, in percent: Mean (2)	Range (3)
Single-Family Residential		
1/4 Acre	30	23-38
1/3 Acre	22	15-30
1/2 Acre	17	9-25
1 Acre	14	8-20
2 Acres	12	7-20
Multi-Family Residential	54	42-65
Commercial	85	51-98
Industrial	59	46-72

General Considerations

1. Infiltration is the movement of water from the land surface into and through the upper horizon of soil. Percolation is the movement of water through the underlying soil or geologic strata subsequent to infiltration. Infiltration can be controlled by percolation if the soil does not have a sustained drainage capacity to provide access for more infiltrated water. However, the extent by which percolation can restrict infiltration for design rainfalls in Arizona needs to be carefully considered. For example, shallow soils with high infiltration rates that overlay nearly impervious material can be placed in hydrologic soil group D in NRCS soil surveys. The soil texture, vegetation cover, and depth of the surface horizon of soil and the properties of the underlying horizons of soil need to be considered when estimating the infiltration rate. Surface soils that are more than 6 inches thick should generally be considered adequate to contain infiltrated rainfall for up to the 100-year rainfall in Arizona without the subsoil restricting the infiltration rate. This is because most common soils have porosities that range from about 25 to 35 percent, and therefore 6 inches of soil with a porosity of 30 percent can absorb about 1.8 inches (6 inches times 30 percent) of rainfall infiltration. It is unlikely that more soil moisture storage is needed for storms up to the 100-year return period in Arizona. Accordingly, in estimating the Green and Ampt infiltration parameters in Arizona, for up to the 100-year rainfall, the top 6 inches of soil should be considered. If the top 6 inch horizon is uniform soil or nearly uniform, then select the Green and Ampt parameters for that soil texture. If the top 6-inch horizon is layered with different soil textures, then select the Green and Ampt parameters for the soil texture with the lowest hydraulic conductivity (XKSAT).

2. Parameter values for design should be based on reasonable estimates of watershed conditions that would minimize rainfall losses. The estimate of impervious area (RTIMP) for urbanizing areas should be based on ultimate development in the watershed.

3. Three sources of information can be used to classify soil texture for the purpose of estimating Green and Ampt infiltration equation parameters. The primary source that can be used for the watershed, when it is available, is the detailed soil surveys that are prepared by the NRCS. When detailed soil surveys are not available for the watershed, then the general soil map and accompanying tables prepared by the NRCS for Arizona (as part of the nationwide survey) are to be used. NRCS soil data can be obtained as follows;

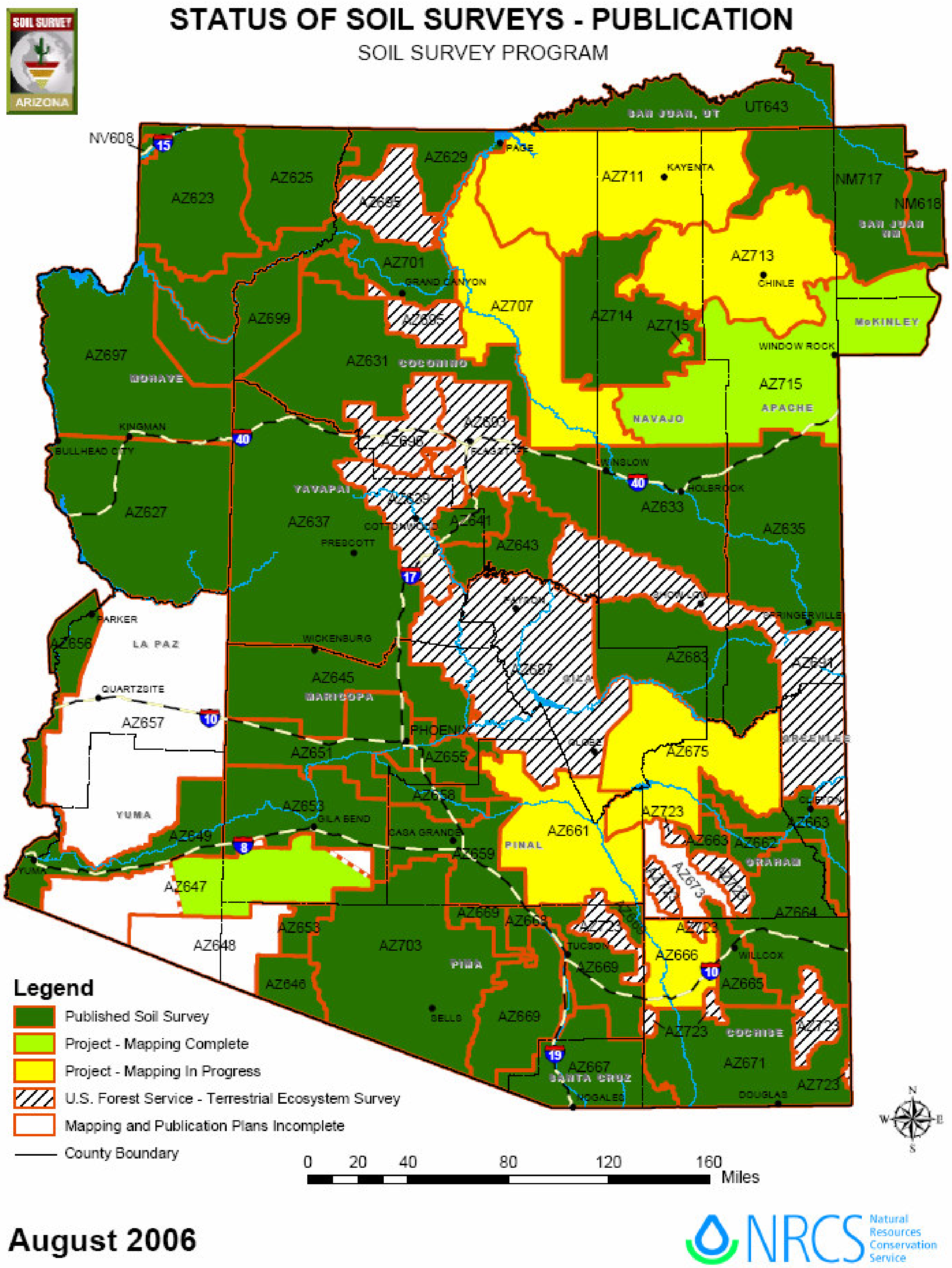
    a. Printed manuscripts of detailed soil surveys are available through the NRCS field offices. Contact information for the field offices can be found at http://soils.usda.gov/. Refer to Figures 9 and 9A for the detailed soil surveys that are available in this form.

    b. Detailed soil survey manuscripts for selected soil surveys are available digitally from: http://soils.usda.gov/survey/online_surveys/arizona/index.html.

    c. Soil map unit boundaries and tabular data for detailed soil surveys as well as the general soil survey are available at http://soildatamart.nrcs.usda.gov/. Refer to Figure 10 for the detail soil surveys that are available digitally.

    The third source of soil information is from the U.S. Forest Service (USFS). The USFS version of the NRCS soil survey (both detailed and general) is the Terrestrial Ecosystem Survey (TES). Terrestrial Ecosystem Surveys have been completed or are in progress for each National Forest in Arizona. In the near future, the USFS will be posting the TES at http://www.fs.fed.us/rs/gis/datasets.shtml.

FIGURE 3.9



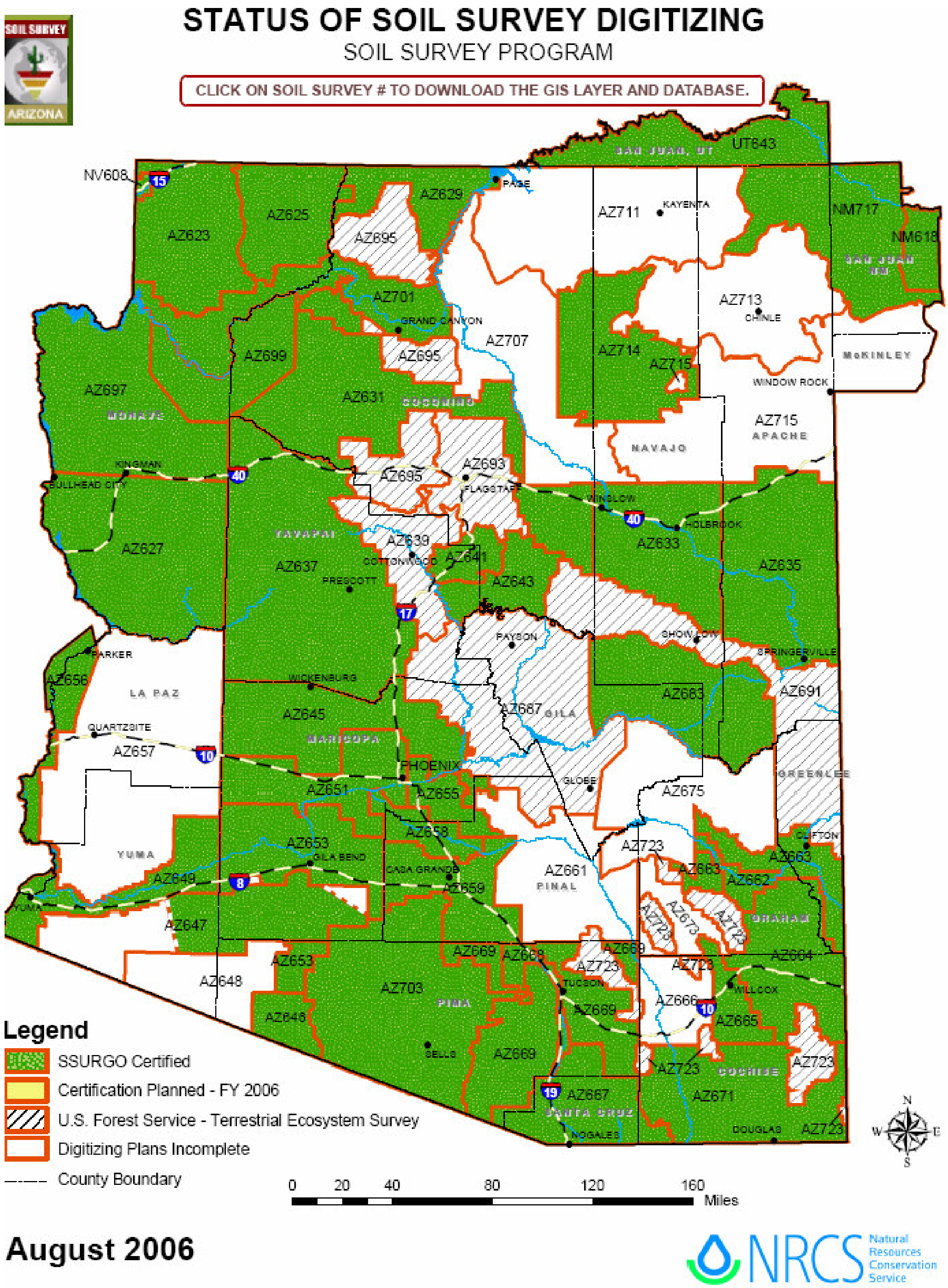
August 2006

FIGURE 3.9A
Soil Survey Areas

	Soil Survey Area Name	Approximate Area (Acres)
NV608	Virgin River Area, NV-AZ, Parts of Clark and Lincoln Counties, NV and Part of Mohave County, AZ	1,068,616
NM618	San Juan County, New Mexico, Eastern Part	315,800
AZ623	Shivwits Area, AZ, Part of Mohave County	1,547,000
AZ625	Mohave County, AZ, Northeastern Part and Part of Coconino County	1,038,145
AZ627	Mohave County, AZ, Southern Part	2,492,300
AZ629	Coconino County Area, AZ, North Kaibab Part	739,050
AZ631	Coconino County Area, AZ, Central Part	2,314,000
AZ633	Navajo County Area, AZ, Central Part	1,504,900
AZ635	Apache County, AZ, Central Part	2,113,800
AZ637	Yavapai County, Western Part	3,774,500
AZ639	Black Hills-Sedona Area, AZ, Parts of Coconino and Yavapai Counties	824,500
AZ641	Beaver Creek Area, AZ	302,205
AZ643	Long Valley Area, AZ	626,623
UT643	Navajo Indian Reservation, San Juan County, Utah	1,335,185
AZ645	Aguila-Carefree Area, Parts of Maricopa and Pinal Counties, AZ	1,629,120
AZ646	Organ Pipe Cactus National Monument, AZ	330,689
AZ647	Luke Air Force Range, AZ, Parts of Maricopa , Pima and Yuma Counties	1,940,000
AZ648	Cabeza Prieta Area, AZ, Parts of Pima and Yuma Counties	909,311
AZ649	Yuma-Wellton Are, Parts of Yuma County, AZ, and Imperial County, CA	1,042,429
AZ651	Maricopa County, AZ, Central Part	1,076,330
AZ653	Gila Bend-Ajo Area, AZ, Parts of Maricopa and Pima Counties	1,432,320
AZ655	Eastern Maricopa and Northern Pinal Counties Area, AZ	348,025
AZ656	Colorado River Indian Reservation, Parts of La Paz County, AZ, and Riverside and San Bernardino Counties, CA	268,850
AZ657	Kofa Area, AZ, Parts of La Paz and Yuma Counties	3,806,931
AZ658	Gila River Indian Reservation, AZ, Parts of Maricopa and Pinal Counties	371,913
AZ659	Pinal County, AZ, Western Part	937,020
AZ661	Eastern Pinal and Southern Gila Counties, AZ	1,
AZ662	Safford Area, AZ	208,500
AZ663	Gila-Duncan Area, AZ, Parts of Graham and Greenlee Counties	770,000
AZ664	San Simeon Area, AZ, Parts of Cochise, Graham and Greenlee Counties	1,220,996

	Soil Survey Area Name	Approximate Area (Acres)
AZ665	Willcox Area, AZ, Parts of Cochise and Graham Counties	367,370
AZ666	Cochise County, AZ, Northwestern Part	625,000
AZ667	Santa Cruz and Parts of Cochise and Pima Counties, AZ	1,098,300
AZ668	Tucson-Avra Valley Area, AZ	214,100
AZ668	Pima County, AZ, Eastern Part	1,900,000
AZ671	Cochise County, AZ, Douglas-Tombstone Part	1,714,300
AZ673	Graham County, AZ, Southwestern Part	410,000
AZ675	San Carlos Indian Reservation, AZ, Parts of Gila and Graham Counties	1,827,421
AZ683	Fort Apache Indian Reservation, AZ, Parts of Apache, Gila and Navajo Counties	1,664,972
AZ687	Tonto National Forest, AZ, Parts of Gila, Maricopa, Pinal and Yavapai Counties	2,873,295
AZ691	Apache-Sitgreaves National Forests, AZ, Parts of Apache, Coconino and Navajo Counties	2,112,320
AZ693	Oak Creek-San Francisco Peaks Area, AZ, Part of Coconino County	859,000
AZ695	Kaibab National Forest, AZ, Parts of Coconino, Mohave and Yavapai Counties	1,554,797
AZ697	Mohave County, AZ, Central Part	2,431,200
AZ699	Hulapai-Havasupai Area, AZ, Parts of Coconino, Mohave and Yavapai Counties	1,180,540
AZ701	Grand Canyon Area, AZ, Parts of Coconino and Mohave Counties	1,450,020
AZ703	Toho O'odham Nation, AZ, Parts of Maricopa, Pima and Pinal Counties	2,855,032
AZ707	Little Colorado River Area, AZ, Parts of Coconino and Navajo Counties	2,240,000
AZ711	Navajo Mountain Area, AZ, Parts of Apache, Coconino and Navajo Counties	2,559,440
AZ713	Chinle Area, Parts of Apache and Navajo Counties, AZ, and San Juan County, NM	1,930,000
AZ714	Hopi Area, AZ, Parts of Coconino and Navajo Counties	1,561,054
AZ715	Fort Defiance Area, Parts of Apache and Navajo Counties, AZ, and McKinley and San Juan Counties, NM	3,210,000
NM717	Shiprock Area, Parts of Apached County, AZ and San Juan County, NM	1,835,230
AZ723	Coronado National Forest, AZ, Parts of Cochise, Graham, Pima and Pinal Counties	1,090,135

FIGURE 3.10


STATUS OF SOIL SURVEY DIGITIZING
SOIL SURVEY PROGRAM
CLICK ON SOIL SURVEY # TO DOWNLOAD THE GIS LAYER AND DATABASE.
SOIL SURVEY
ARIZONA
NV608
AZ623
AZ625
AZ695
AZ629
PAGE
SAN JUAN, UT
UT643
AZ711
KAYENTA
NM717
NM618
SAN JUAN NM
AZ701
GRAND CANYON
AZ713
CHINLE
AZ699
AZ707
AZ714
AZ715
MCKINLEY
AZ697
MOHAVE
AZ631
COCONINO
WINDOW ROCK
APACHE
NAVAJO
KINGMAN
BULLHEAD CITY
AZ693
FLAGSTAFF
WINSLOW
HOLBROOK
AZ627
YAVAPAI
AZ639
AZ641
AZ633
AZ635
AZ637
COTTONWOOD
PRESCOTT
AZ643
PAYSON
SHOW LOW
SPRINGERVILLE
PARKER
AZ656
LA PAZ
WICKENBURG
AZ645
AZ687
GILA
AZ683
AZ691
QUARTZSITE
AZ657
MARICOPA
PHOENIX
GLOBE
AZ675
GREENLEE
AZ651
AZ655
AZ658
AZ653
GILA BEND
CASA GRANDE
AZ659
AZ661
PINAL
AZ723
AZ663
AZ662
CLIFTON
YUMA
AZ649
AZ647
AZ673
GRAHAM
AZ669
AZ668
AZ664
AZ648
AZ703
PIMA
TUCSON
WILLCOX
AZ646
AZ666
AZ665
SELLS
AZ667
SANTA CRUZ
NOGALES
COCHISE
AZ671
DOUGLAS
Legend
SSURGO Certified
Certification Planned - FY 2006
U.S. Forest Service - Terrestrial Ecosystem Survey
Digitizing Plans Incomplete
County Boundary
0 20 40 80 120 160
Miles
N
W
E
S
August 2006
NRCS
Natural Resources Conservation Service

4. Most drainage areas or modeling subbasins will be composed of several subareas containing soils of different texture; and therefore, there may be the need to determine composite values for the Green and Ampt parameters to be applied to the drainage areas or each modeling subbasin. The procedure that is to be used is to average the area-weighted logarithms of the individual subarea XKSAT values and to select the PSIF and DTHETA values from a graph.

   The composite XKSAT is calculated by Equation 3.1:

$$\overline{XKSAT} = \left(\frac{antilog\, \Sigma\, A_i \log XKSAT_i}{A_T} \right) \tag{3.1}$$

   Where $\overline{\text{XKSAT}}$ = composite hydraulic conductivity (XKSAT), in inches/hour,

   $XKSAT_i$ = hydraulic conductivity of the soil in a subarea, in inches/hour.

   A_i = size of a subarea, and

   A_T = size of the drainage area or modeling subbasin.

   After $\overline{\text{XKSAT}}$ is calculated, the values of PSIF and DTHETA (normal or dry) are selected from Figure 7 at the corresponding value of $\overline{\text{XKSAT}}$.

5. The composite values for PSIF and DTHETA are determined from the composite value of XKSAT <u>prior</u> to making the correction of XKSAT for vegetation cover. Correction of XKSAT for vegetation cover is made <u>after</u> the composite value of XKSAT is determined.

<u>Procedures</u>

Initial Losses (IA)

1. Delineate areas of each unique land form/use within the watershed.

2. Assign values of IA to each land form/use using Table 3.3.

3. Calculate the area of each unique land form/use within each subbasin.

4. Calculate the area weighted IA for each subbasin.

Green and Ampt Infiltration Equation Parameters (XKSAT, DTHETA and PSIF)

1. Assign soil texture and XKSAT to each soil map unit within the watershed.

   Note: This process has been completed for each soil map unit of the general soil survey and is provided in Appendix B. This information should only be used where detailed soil surveys are not available.

   a. Read the description of each of the soil series and each mapping unit. Try to identify the soil texture that best describes each soil (or the top 6 inches of layered soils).

b. Consult soil properties tables of the soil survey, and from the columns for soil depth and dominant texture, make the final selection of soil texture that will control the infiltration rate. The size gradation data that is provided in the tables can also be used to assist in selecting the soil texture. Many of the soils in Arizona contain significant quantities of gravel, and the adjective “gravelly”, when used in conjunction with the soil texture, can either be disregarded when it is used in conjunction with “sandy”, that is, gravelly sandy loam can be taken as equivalent to sandy loam; or “gravelly” can be used as a replacement for “sandy” when used alone, that is, gravelly clay can be taken as equivalent to sandy clay. Similarly, adjectives such as “very fine” and “very coarse”, usually used in association with sand, can be disregarded in determining soil texture classification.

c. Look up the bare ground XKSAT value for each assigned soil texture form Table 3.4.

2. If the drainage area or subbasin consists of soil of the same textural class, then select PSIF and DTHETA (dry, normal or saturated) for that soil texture from Table 3.4. Proceed to Step 4.

3. If the drainage area or subbasin consists of subareas of different soil textural classes, then calculate the composite value of XKSAT using Equation 3.1, and select the composite values of PSIF and DTHETA using Figure 7 If appropriate, area weight DTHETA.

4. Estimate the percent vegetation cover for the drainage area or each subbasin and determine the hydraulic conductivity (XKSAT) correction factor (C_k) using Figure 8. Apply correction factors (C_k) to the value of XKSAT.

Impervious Area (RTIMP)

1. Assign values of effective impervious area for each land use within the watershed using Table 3.5.

2. Assign values of effective rock outcropping (if any) from the soils information.

3. Calculate the area weighted average RTIMP for each subbasin.

Applications and Limitations

The Green and Ampt infiltration equation, along with an estimate of the surface retention loss can be used to estimate rainfall losses for most areas of Arizona with confidence. Most soils in Arizona are loamy sand, sandy loam, loam, or silt loam for which the Green and Ampt infiltration equation parameters from Table 3-4 should apply. Silt, as a soil texture, is relatively rare and it is not expected that significant areas will be encountered. The finer soil textures (those with “clay” in the classification name) occur in Arizona, but not usually over large areas; however, these soils have relatively low infiltration rates (XKSAT). Use of the Green and Ampt infiltration equation parameters for the finer soil textures may be somewhat conservative, and therefore their use should be appropriate for most design flood estimation purposes. Sand and volcanic cinder, as a soil texture, are also relatively rare and have very high infiltration rates (XKSAT). Therefore, when encountering large areas of these classifications it is possible that estimates of rainfall losses with the Green and Ampt equation would be too large and an alternative method should be used. Refer to sections from the ADOT Hydrology Manual in Appendix C for discussion of the Initial Loss plus Uniform Loss Rate method as an appropriate alternative method.

3.4.3 Unit Hydrographs

General

A unit hydrograph is defined as the hydrograph of one inch of direct runoff from a storm of a specified duration for a particular watershed. Every watershed will have a different unit hydrograph that reflects the physiography, topography, land-use, and other unique characteristics of the individual watershed. Different unit hydrographs will be produced for the same watershed for different durations of rainfall excess. For example, a unit hydrograph for a particular watershed can be developed for a rainfall excess duration of 5-minutes, or 15-minutes, or 1-hour, or 6-hours, etc. Any duration can be selected for unit hydrograph development as long as an upper limit for the unit hydrograph duration is not exceeded.

Only a few watersheds in Arizona will have an adequate database (rainfall and runoff records) from which to develop unit hydrographs. Therefore, indirect methods usually will be used to develop unit hydrographs. Such unit hydrographs are called synthetic unit hydrographs.

The unit hydrograph itself is a lumped parameter in that it represents the composite effects of all of the watershed and storm characteristics that dictate the rate of rainfall excess runoff from the watershed. Although there are numerous watershed and storm characteristics that determine the shape of a unit hydrograph, only a limited number of those characteristics can be quantified and used to calculate a unit hydrograph. One or more unit hydrograph parameters (depending on the selection of synthetic unit hydrograph procedure) are needed to calculate a unit hydrograph.

The concept of the unit hydrograph is used to route the time increments of rainfall excess from the watershed (or modeling subbasin) to the watershed outlet (or modeling concentration point). A synthetic unit hydrograph procedure that can be used is the Clark unit hydrograph.

Method

The Clark unit hydrograph requires the estimation of three parameters; the time of concentration (T_c), the storage coefficient (R), and a time-area relation. Time of concentration is also used to select the storm duration and computation interval (NMIN).

Time of concentration is the travel time, during the corresponding period of most intense rainfall excess, for a floodwave to travel from the hydraulically most distant point in the watershed to the point of interest (concentration point). Three time of concentration (T_c) equations are to be used depending on the type of watershed; desert/mountain, agricultural fields, or urban.

Desert/Mountain

$$T_c = 2.4\ A^{.1}\ L^{.25}\ L_{ca}^{.25}\ S^{-.2} \qquad (3.2)$$

Agricultural Fields

$$T_c = 7.2\ A^{.1}\ L^{.25}\ L_{ca}^{.25}\ S^{-.2} \qquad (3.3)$$

Urban

$$T_c = 3.2\ A^{.1}\ L^{.25}\ L_{ca}^{.25}\ S^{-.14}\ RTIMP^{-.36} \quad (3.4)$$

Where,

T_c	=	time of concentration, in hours
A	=	area, in square miles
S	=	watercourse slope, in ft/mile
L	=	length of watercourse to the hydraulically most distant point, in miles
L_{ca}	=	length measured from the concentration point along L to a point on L that is perpendicular to the watershed centroid, in miles
RTIMP	=	effective impervious area, in percent.

In using Equations 3.2 through 3.4, the following points should be noted and observed:

1. The area (A) will be determined from the best available map. The delineation of the drainage boundary needs to be carefully performed, and special care must be taken where there is little topographic relief. In urban areas, land grading and road construction can produce drainage boundaries that separate runoff from contributing areas during small and lower intensity storms. However, larger and more intense storms, such as the design storm from this State Standard attachment, can produce runoff depths that can cross these intermediate drainage boundaries resulting in a larger total contributing area. Similarly, floods on alluvial fans (active and inactive) and in distributary flow systems can result in increased contributing areas during larger and more intense storms. For such areas, it is generally prudent to consider the largest reasonable drainage area in these situations.

2. Determination of the hydraulically most distant point will define both L and S. Often, the hydraulically most distant point is determined as the point along the watershed boundary that has the longest flow path to the watershed outlet (or subbasin concentration point). This is generally true where the topography is relatively uniform throughout the watershed. However, there are situations where the longest flow path (L) does not define the hydraulically most distant point. Occasionally, especially in mountainous areas, a point with a shorter flow path may have an appreciably flatter slope (S) such that the shorter flow path defines the hydraulically most distant point. For watersheds with multiple choices for the hydraulically most distant point, the T_c should be calculated for each point and the largest T_c should be used.

3. Slope (S) is the average slope calculated by dividing the difference in elevation between the hydraulically most distant point and the watershed outlet by the watercourse length (L). This method will usually be used to calculate S. However, there are situations where special consideration should be given to calculating S and to dividing the watershed into subbasins. For example, if there is dramatic change in watercourse slope throughout the watershed, then the use of a multiple subbasin model should be considered with change in watercourse slope used in delineating the subbasins. There will also be situations where the watercourse contains vertical or nearly vertical drops (mountain rims, headcuts, rock outcrop, and so forth). In these situations, plotting of the watercourse profile will usually identify nearly vertical changes in the channel bed. When calculating the average slope, subtract the accumulative elevation differential that occurs in

nearly vertical drops from the overall elevation differential prior to calculating S.

4. L_{ca} is measured along L from the watershed outlet to a point on L that is essentially perpendicular to the watershed centroid. This is a shape factor in the T_c equation. Occasionally, the shape of agricultural fields or urban subbasins are nearly rectangular in shape and this may result in two different dimensions for L_{ca}. In the case of such nearly rectangular (and therefore, nearly symmetrical) watersheds or subbasins L_{ca} can usually be satisfactorily estimated as ½ L.

5. RTIMP is the effective impervious area. This is the same value that was determined for the watershed by the procedures in the Rainfall Losses section. RTIMP is used to estimate T_c for urban watersheds only (Equation 3.4).

6. Ideally, the selection of the watershed or subbasin boundaries can be made so that the area represents a hydrologically uniform region that is essentially all desert/mountain, or agricultural fields, or urban, and for those situations, the T_c equations (3.2 through 3.4) can be applied directly. However, there will be situations where the watershed or modeling subbasin is a mixture of two or three of those types. In those cases, the T_c equation is selected based on the watershed type that contains the greatest portion of L. The effects of a mixture of watershed types are accounted for by the selection of the time-area relation (to be discussed in a later section).

The storage coefficient is a Clark unit hydrograph parameter that relates the effects of direct runoff storage in the watershed to unit hydrograph shape. The equation for estimating the storage coefficient (R) is:

$$R = 0.37\ T_c^{1.11}\ L^{.80}\ A^{-.57} \tag{3.5}$$

Where R is in hours and the variables are as defined for the T_c equations.

The time-area relation is a graphical parameter that specifies the accumulated area of the watershed that is contributing runoff to the outlet of the watershed at any time. Two methods can be used to develop a time-area relation: 1) by analysis of the watershed to define incremental runoff producing areas that have equal incremental travel times to the outflow location, or 2) by use of synthetic time-area relations. The development of a time-area relation by analysis of the watershed is a difficult task and well-defined and reliable procedures for this task are not available. Unless the watershed has an extremely unusual shape, or has several distinct areas of dramatically different land-use, this analysis should not be undertaken. In general, synthetic time-area relations can be used in Arizona.

The dimensionless, synthetic time-area relations that can be used in Arizona are shown in Figure 11 and the coordinate values of the curves are listed in Table 3.6. Curve A should be used if the land-use in the watershed or subbasin is urban or predominantly urban. Curve C should be used if the land-use in the watershed or subbasin is desert-rangeland or is mostly desert/rangeland with some mountains in the watershed and/or some irrigated agricultural fields interspersed in the lowlands. Curve B should be used for all other situations.

Curves A and C are representative of several time-area relations reconstituted from runoff events on watersheds in the Southwestern U.S. Those relations, along with the hydrologic characteristics of the watersheds are provided in Appendix D and may be used if the study watershed is hydrologically similar to the watershed from which the time-area relation is based. Curve B is the default time-area relation in HEC-1 and will be used with the Clark unit hydrograph if a time-area relation (UA record) is not supplied. Curves A and C are dimensionless and the curves are input to HEC-1 by inserting the percent of total area values from Table 3.6 in the UA record.

Duration

The duration of the unit hydrograph (or all unit hydrographs in a multiple subbasin model) is specified in HEC-1 in the IT record as NMIN. In general, NMIN will be selected according to the following criteria:

NMIN = 2 minutes for 3- and 6-hour storm durations and
NMIN = 5 minutes for a 24-hour storm duration
Note: NMIN should not exceed .25 T_c for the subbasin with the shortest T_c.

However, there may be special situations where a NMIN, other than as defined above, is to be used. In those situations, the following rules should be considered:

1. NMIN = 0.15 T_c provides adequate definition of the hydrograph peak with an optimum number of hydrograph coordinate calculations.
2. NMIN = 0.25 T_c is the maximum value for NMIN.
3. NMIN for a multiple subbasin model should be selected based on the smallest T_c value for any of the subbasins in the model.

Selection of the storm duration is a function of the watershed T_C. Storm durations to be used are either 3, 6, or 24 hours. In general, storm duration will be selected according to the following (for borderline T_c compute both storm durations and use the higher value) :

1. Storm duration = 3 hours for watershed $T_C < 2.5$ hours
2. Storm duration = 6 hours for 2.5 hours $\leq$ watershed $T_C < 5$ hours
3. Storm duration = 24 hours for watershed $T_C \geq 5$ hours

Table 3.6
Values of the Dimensionless Synthetic
Time-Area Relations for the Clark Unit Hydrograph
(Source: ADOT Hydrology Manual)

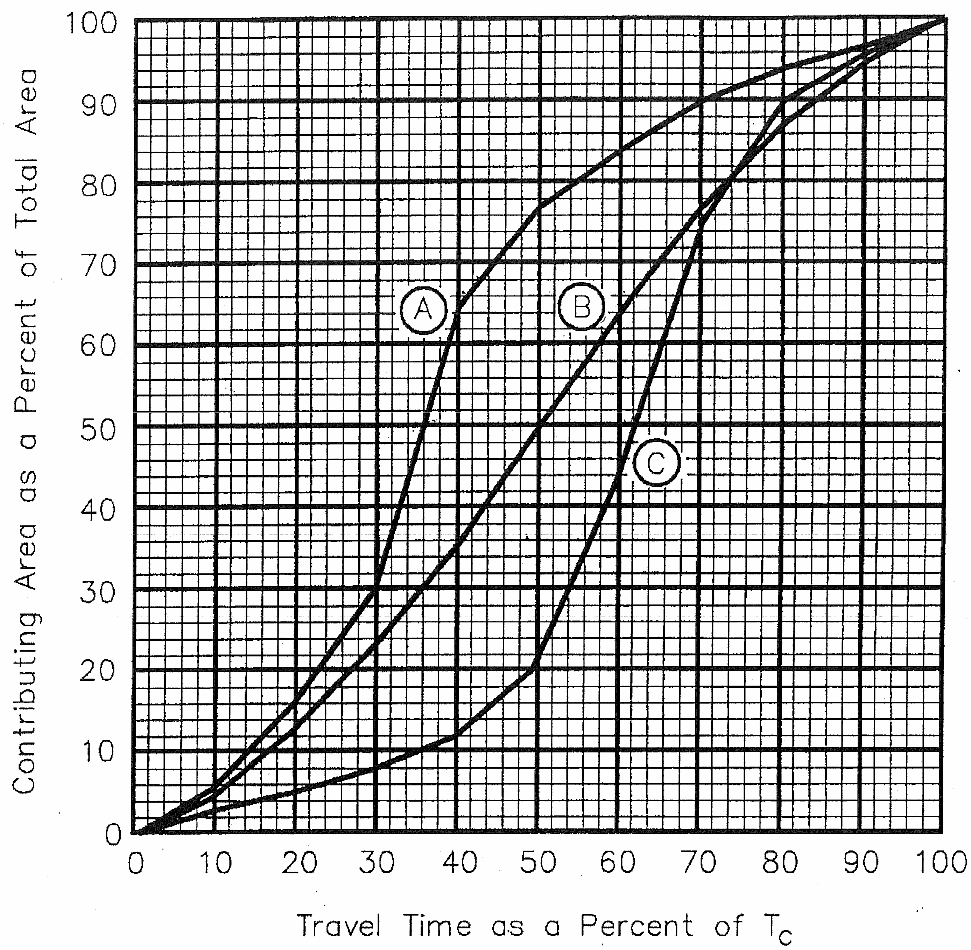
	Contributing Area, as a Percent of Total Area[a]		
Travel Time, as a percent of T_c (1)	A (2)	B[b] (3)	C (4)
0	0	0.0	0
10	5	4.5	3
20	16	12.6	5
30	30	23.2	8
40	65	35.8	12
50	77	50.0	20
60	84	64.2	43
70	90	76.8	75
80	94	87.4	90
90	97	95.5	96
100	100	100.0	100

[a] – The dimensionless Synthetic Time-Area relations should be selected as follows:

A – The land-use in the watershed or subbasin is urban or predominantly urban.
B – All watersheds or subbasins other than those defined for use of curves A or C.
C – The land-use in the watershed or subbasin is desert/rangeland or is mostly desert/rangeland with some mountains in the watershed and/or some irrigated agricultural fields interspersed in the lowlands.

[b] – Curve B is the HEC-1 default Time-Area relation and the UA record is not needed as input to the HEC-1 model.

FIGURE 3.11
SYNTHETIC TIME-AREA RELATION



Curve A– Urban
Curve B– HEC–1 Default Relation
Curve C– Desert/Rangeland

Procedure

1. Delineate the watershed boundaries on the watershed base map.

2. Trace the paths of the major watercourses in the watershed on the base map.

3. If the watershed has more than one land-use, define the areas of the different land-use types:

   Urban
   Desert/Rangeland
   Mountain
   Irrigated Agriculture

4. Determine whether the watershed can be treated as a single, hydrologically homogeneous watershed, or if it must be divided into modeling subbasins. This decision should consider the following factors:

   a. Topography (and channel slope),
   b. Land-use,
   c. Diversity of soil texture (from Rainfall Losses sectio),
   d. Occurrence of rock outcrop,
   e. Existence of drainage and flow control structures within the watershed (detention/retention basins, elevated highway cross-drainage structures, channelized and improved watercourses, etc.),
   f. Shape of the watershed, and
   g. Needs of the hydrologic model, such as investigation and planning for future highway drainage structures.

5. If the watershed is to be divided into modeling subbasins, use the information from Steps 2, 3, and 4 to delineate the subbasin boundaries.

6. For the watershed and each modeling subbasin, determine the following:

   A - area, in square miles,
   L - length of the flow path to the hydraulically most distant point, in miles
   L_{ca} - length along L to a point opposite the centroid, in miles
   S - average slope of L, in ft/mile
   RTIMP - effective impervious area, in percent.

7. Calculate T_c depending on the type of watershed and each subbasin

   Desert/mountain

   $$T_c = 2.4\ A^{.1}\ L^{.25}\ L_{ca}^{.25}\ S^{-.2}$$

   Agricultural Fields

   $$T_c = 7.2\ A^{.1}\ L^{.25}\ L_{ca}^{.25}\ S^{-.2}$$

Urban

$$T_c = 3.2\ A^{.1}\ L^{.25}\ L_{ca}^{.25}\ S^{-.14}\ RTIMP^{-.36}$$

From the watershed T_C select the appropriate storm duration.

8. Calculate R for the watershed or each subbasin

$$R = 0.37\ T_c^{1.11}\ L^{.80}\ A^{-.57}$$

9. Enter the values of T_c and R in the UC record for the watershed or each subbasin.

10. Determine whether the time-area relation will be developed from an analysis of the watershed or whether dimensionless synthetic time-area relation will be used.

    a. If the time-area relation is to be determined by analytic means, proceed with the analysis and input the incremental areas (or percentages or total area) in the UA record.

    b. If the dimensionless synthetic time-area relations are to be used

        i. Use the values for Curve A in the UA record if the watershed or subbasin is urban or predominantly urban,

        ii. Use the values for Curve C in the UA record if the watershed or subbasin is desert/rangeland with some mountains and/or some irrigated agricultural fields interspersed in the lowlands, and

        iii. Use Curve B for all other applications (Curve B is the HEC-1 default relation and the UA record is not needed).

<u>Applications and Limitations</u>

The Clark unit hydrograph, as described herein, can be used for virtually any watershed that will be encountered in Arizona. Section 3.3.5 addresses rainfall distribution procedures for various flood frequency events, however this Standard was developed for the 100-year frequency event and does not address all issues necessary to evaluate other frequency events. Equations 3.2 through 3.4 were derived for use in estimating the time of concentration for floods with design return periods that are typical for highway drainage structures (25-year to 100-year). Use of these equations may result in time of concentration estimates that are too short for floods of return period less than 25-year and too long for floods of return period appreciably greater than 100-year. This is because of the effect that runoff magnitude has on the hydraulic efficiency (runoff velocity) of watersheds. Therefore, if Equations 3.2 through 3.4 are used to estimate the time of concentration for floods of return period appreciably greater than 100-year, then the time of concentration should be reduced (by as much as 25 percent for very large, rare floods); similarly, for estimating the time of concentration for floods of return period less than the 25-year, then the time of concentration should be increased (by as much as 100 percent for very frequent flooding, such as the 2-year). Since R (Equation 3.5) is a function of T_c, the R Value should be recalculated if T_c is adjusted for return period.

3.5 Channel Routing

3.5.1 General

Channel routing describes the movement of a flood wave (hydrograph) down a watercourse. For most natural rivers, as a flood wave passes through a given reach, the peak of the outflow hydrograph is usually attenuated and delayed due to flow resistance in the channel and the storage capacity of the river reach. In urban environments, runoff is often conveyed in man made features such as roadways, storm drains and engineered channels that minimize hydrograph attenuation.

Channel routing is used in flood hydrology models, such as HEC-1, when the watershed is modeled with multiple subbasins and runoff from the upper subbasins must be routed through a channel, or system of channels, to the watershed outlet. Several methods are available for channel routing. The method that is recommended for the majority of natural riverine conditions is the Modified Puls method. For the majority of urban conditions, the recommended method is Kinematic Wave routing.

3.5.2 Method

Modified Puls

Modified Puls is a storage routing method. In HEC-1, it can be applied using a stage-storage-discharge relation or a normal depth storage-outflow relation. Typically, the stage-storage-discharge relation is used for reservoir routing purposes (e.g. detention/retention basins). The normal depth storage-outflow relation is generally used for channel routing purposes.

Hydrograph attenuation is estimated by treating the given reach as a series of small storage elements, sub-reaches. Outflow from upstream sub-reaches become the inflow to the downstream sub-reach. Outflow from each sub-reach is estimated using a form of the continuity equation (USACE, 1990). For the stage-storage-discharge relation option, the solution of the outflow from each sub-reach is controlled by the supplied relation. Solution of the outflow from each sub-reach by the normal depth option is controlled by the storage outflow relation that, in HEC-1, is determined from the supplied channel properties; length, slope, roughness and cross sectional geometry.

Kinematic Wave

The Kinematic Wave method, as implemented in HEC-1, is a simplified form of the equations of motion (USACE, 1979). A basic assumption inherent to this method is that bed slope equals friction slope. The Kinematic Wave method is formulated for a discrete set of predefined geometric conveyance elements.

- Circular
- Triangular
- Rectangular
- Trapezoidal

The solution of the simplified form of the equations of motion is accomplished using a finite difference approximation. The finite difference approximation relies on the discretization of the reach by time as well as length.

3.5.3 General Considerations

Modified Puls

Both the stage-storage-discharge relation and normal depth storage-outflow relation options can be used for channel routing. In fact, both options will yield the same results if constructed from the same set of representative physical conditions. For most natural watercourses, the normal depth option is recommended. Use of the stage-storage-discharge relation option is only recommended for natural rivers that have and/or require consideration of storage due to backwater conditions or for braided watercourses where the specification of representative cross sectional geometry is not practical. Note that the Modified Puls method is the only channel routing method (in HEC-1) than can reflect additional storage due to backwater conditions. This can only be accomplished, however, through external calculations (such as can be done using HEC-RAS) and formulating the results into a stage-storage-discharge relation.

The amount of hydrograph attenuation is a function of the number of sub-reaches needed to simulate the movement of the floodwave through the reach. The number of sub-reaches is a function of the distance that a floodwave can travel in one computation time interval. Selection of too few sub-reaches (referred to in HEC-1 as the number of computation steps, NSTPS) can artificially increase attenuation. Selection of too many sub-reaches can artificially decrease attenuation. Thus, NSTPS is ideally a calibration parameter (USACE, 1990). In the estimation of NSTPS, it is important to recognize that floodwave velocity is greater than average velocity. For most natural watercourses, a ratio of the floodwave velocity to average velocity of 1.5 can be used (USACE, 1990). Ratios for other, generic channel shapes are listed in Table 3.7.

Table 3.7
Ratios of Floodwave Velocity to Average Velocity
(Source: River Routing with HEC-1 and HEC-2, USACE, 1990)

Channel Shape	Ratio
Wide rectangular	1.67
Wide parabolic	1.44
Triangular	1.33

The initial flow conditions must be specified to start the routing computations. Normally the initial condition that is used is the discharge in the channel and this will often be 0.0 (dry channel) for channels in Arizona. If the channel is expected to have flow in the channel prior to the modeled storm, or a baseflow, then use the appropriate discharge data. The channel water surface elevation at the start of the routing computation can be used, if desired instead of initial discharge conditions.

Use of the Normal Depth option requires input of the energy grade line slope. The slope of the energy grade line is not normally known. For normal flow, it is parallel to the channel bed slope. It is usually estimated as the channel bed slope, calculated by dividing the difference in bed elevation between the upper and lower ends of the watercourse by the routing reach length.

Use of the Normal Depth option also requires input of the channel roughness. The Manning's roughness coefficient, n, is a measure of the flow resistance of a channel or overbank flow area. The flow resistance is affected by many factors including size of bed material, bed form, irregularities in the cross section, depth of flow, vegetation, channel alignment, channel shape, obstructions to flow, and quantity of sediment being transported in suspension or as bed load. In general, all factors that retard flow and increase turbulent mixing tend to increase n. Typical values of n are listed in Table 3.8. A detail procedure to estimate n is provided in Appendix E.

TABLE 3.8
BASE VALUES (n_0) OF MANNING'S ROUGHNESS COEFFICIENT
FOR STRAIGHT, UNIFORM, STABLE CHANNELS
(from Thomsen and Hjalmarson, 1991)

Channel Material	**Size of Bed Material**		**Base Values, n_0**	
	Millimeters	**Inches**	**Benson and Dalrymple (1967)[a]**	**Chow (1959)[b]**
Concrete	-------	-------	0.012-0.018	0.011
Rock Cut	-------	-------	-------	.025
Firm Soil	-------	-------	.025-.032	.020
Coarse Sand	1-2	-------	.026-.035	-------
Fine Gravel	-------	-------	-------	.024
Gravel	2-64	0.08-2.5	.028-.035	-------
Coarse Gravel	-------	-------	-------	.028
Cobble	64-256	2.50-10.0	.030-.050	-------
Boulder	>256	>10.0	.040-.070	-------

[a]Straight uniform channel.
[b]Smoothest channel attainable in indicated material.

The channel geometry used in the Normal Depth option is limited to an 8-point cross section. That cross section is to be representative of the hydraulic characteristics throughout the routing reach. Considerable judgement is necessary in defining the representative 8-point cross section. The guidance in the HEC-1 User's Manual should be followed when defining an 8-point cross section. The coordinates (X and Y) can be to any base datum. Specifically, the vertical dimensions (Y) do not need to correspond to land surface elevation or any elevation for any location along the routing reach.

Kinematic Wave

In general, the physical characteristics required for the Kinematic Wave method are similar to those required for the normal depth option of the Modified Puls method. As such, the discussion of general considerations for the normal depth option applies to the Kinematic Wave method with a few important distinctions. The Kinmatic Wave method only provides hydrograph translation, no attenuation. The amount of translation is determined from the physical characteristic of the reach and the number of routing increments (sub-reaches).

The number of sub-reaches is an important parameter that is directly related to the computational stability. In, HEC-1, the number of sub-reaches is calculated internally but can be overrided by user input. HEC-1 reports the calculation error for each Kinematic Wave routing reach at the end of the output file. This information should be reviewed to determine the appropriateness of the number of sub-reaches. If the calculation error is high, increase the number of sub-reaches. Another or additional mechanism to reduce the calculation error is to adjust (typically decrease) the computation time interval (NMIN). For most instances, it is recommended that NMIN be adjusted first, and then only if necessary should the number of sub-reaches be specified. The numeric stability of the Kinematic Wave method can be particularly problematic when using the circular geometry option. The Kinematic Wave method is for open channel flow conditions regardless of the geometric constraint. If the inflow to the routing reach exceeds approximately 90% of the circular section conveyance capacity, the program simply assumes that the capacity increases without any upper limit (USACE, 1979).

3.5.4 Procedures

1. From the watershed base map, identify the routing reaches.

2. Compile information on the characteristics of those reaches (detailed topographic maps to define channel geometry, photographs of the channels and overbanks, other hydrologic reports for the area, etc.)

3. Conduct a field reconnaissance of the watershed and routing reaches, if practical. Observe and note the characteristics of the routing reaches; variations in the channel cross-sections, irregularity of the channel, and degree of meandering of the main channel. Determine the hydraulically representative section of the routing reaches. Make note of and photograph the representative sections, paying particular attention to flow resistance characteristics; bed material, obstructions to flow (rock outcrop, boulders, debris, etc.), and vegetation in the channel and overbank floodplains. If adequate maps are not available to define the channel geometry of the representative sections, field surveys or field measurements can be made of the channel overbank floodplains.

4. Measure the routing reach length, RLNTH, from the base map.

5. Estimate the energy gradient (SEL), by calculating the channel bed slope from the base map.

6. Prepare a sketch of the representative section of each routing reach. For the normal depth option of the Modified Puls routing method prepare the 8-point cross section geometry and code on the RX and RY records. For the Kinematic Wave routing method select an appropriate geometric shape and code the required data

   - Circular: diameter
   - Deep (rectangular): bottom width
   - Trapezoidal/triangular: bottom width and side slope

7. Estimate a representative roughness coefficient, using Table 3.8. For the normal depth option of the Modified Puls method estimate representative roughness coefficients for the channel and left overbank, if different.

8. For the normal depth option of the Modified Puls-method, estimate the number of sub-reaches.

9. Run the model and review the output.

   For the normal depth option of the Modified Puls method compare the time to peak of the inflow hydrograph to the time to peak of the routed hydrograph. Compute the number of sub-reaches (NSTPS)

$$NSTPS = \frac{\Delta T_p}{NMIN}$$

   Adjust NSTPS for each routing reach as necessary and repeat this step until the estimated NSTPS equals the calculated value.

   For the Kinematic Wave method, review the continuity summary at the end of the output file. If the percent error is greater than one, reduce the model computation time interval (NMIN). If the computational stability does not improve, consider adjusting the number of sub-reaches or using a different routing method.

3.5.5 Applications and Limitations

Channel routing is to be used in multiple subbasin models when the runoff from the upper subbasins passes through a watercourse, or a system of watercourses, to the watershed outlet. Routing should be used in models when a major component of watershed runoff (and inflow hydrograph) enters a relatively long channel and must flow though that channel to the watershed outlet or to a point along the channel where a flood hydrograph is desired. In those situations, the peak of the outflow hydrograph is usually attenuated and delayed compared with that of the inflow hydrograph.

The Normal Depth method of the Modified Puls, that is available in the HEC-1 program, is usually an appropriate routing method for use in watercourses in Arizona. It should be used where routing effects (peak attenuation and delay) are expected. The Kinematic Wave channel routing method can often be used with comparable accuracy for constructed urban channels, including storm drains, and for short, steep natural channels, where routing effects are not expected.

One of the most critical aspects of watershed modeling using subbasins and channel routing is the selection of channel routing lengths (RLNTH). The numeric procedure used in routing calculations requires that the travel time through each routing reach be a multiple of the selected computation interval (NMIN). For this reason, the selection of too short a RLNTH could result in the computation of zero travel time through the routing reach (instantaneous translation of the flood wave through the reach). This could result in erroneously large peak discharges at downstream concentration points in the watershed model. A watershed model of numerous small subbasins and connecting short routing reaches can result in progressively larger overestimation of peak discharge at the watershed outlet.

3.6 Storage Routing

Another situation, which often arises in watershed modeling, is accounting for the existence of a flood storage facility such as a detention basin, lake, pond, or impoundment behind a dam. Data for such facilities can be entered into the watershed model to account for the effect of the flood storage on downstream hydrographs.

As with Channel Routing (see previous section), Storage Routing is indicated with an RS record. Enter 1 for NSTEPS (field 1) and STOR for ITYP (field 2). Fields 3 and 4 can be left blank. The rest of the Storage Routing component is provided using the SA, SE and SQ records. These records provide a table of data with the storage facility surface area, in acres (SA record), elevation, in feet (SE record) and outflow rate, in cfs (SQ record) for the storage facility. The data are provided in sets with the data in each record for field 1 corresponding to the same elevation in the storage facility. For example;

SA	0	20	40
SE	0	1	2
SQ	0	100	200

In the example input above, the storage facility has a surface area of 20 acres and an outflow rate (through a weir or other structure) of 100 cfs, both at an elevation of 1 foot. It will be necessary for the modeler to measure the storage facility areas and determine the stage-outflow characteristics of the outflow structure to prepare the storage routing input data.

The HEC-1 program calculates storage facility volume from the values entered on the SA and SE records. However, if desired, the modeler can use the SV record instead of the SA record, and provide storage facility volumes (in acre feet) directly into the model.

As with all HEC-1 modeling components, the storage routing component is preceded by a KK record (and KM record if desired).

3.7 Hydrograph Combinations

In the process of creating the watershed model it will become necessary to combine two or more parts (components) of the model. For instance, if your model includes two subbasins representing two tributaries meeting at a common point (confluence), it will be necessary to combine the hydrographs generated by each subbasin. It may also be necessary to combine a hydrograph that has been routed from further upstream using the Normal Depth routing routine.

In such cases, components are combined using the HC record. The only input variable on the HC record is ICOMP (field 1, see example input file). This is the number of hydrographs being combined (limit of 5). If for some reason it is necessary to combine more than 5 hydrographs at one location, use successive HC records.

The standard of practice in hydrologic models is to assume storms are stationary, however note that the movement of a storm may affect hydrograph combinations.

3.8 Diversions

In certain circumstances it may become necessary to divert a portion of a hydrograph out of the system. A good example of such a situation would be where a storm drain or diversion channel takes only a portion of the flow being modeled (e.g., accounting for a 25-year capacity storm drain within a HEC-1 model for a 100-year storm). Such situations can be accounted for in the model using the DT, DI and DQ records. These records are explained below. Note that a HEC-1 model may not be the best model to characterize flow diversion in distributary flow areas or alluvial fans.

DT record: Field 1 of this record provides a unique identifier for the hydrograph to be diverted. Fields 2 and 3 can be left blank (see HEC-1 users manual for discussion of applicability of these two fields).

DI and DQ records: These two records work in tandem to provide a table of inflow and diversion flow data. Fields 1 through 10 of the DI record provides inflow values associated with the diversion. The corresponding fields of the DQ record identify how much flow is diverted. For example if you are preparing a model where peak flow may vary up to 500 cfs and a storm drain carries a relatively constant flow of 100 cfs, the DI and DQ records could look like the following:

DI	0	100	200	300	400	500
DQ	0	100	100	100	100	100

If, on the other hand, a diversion structure (such as a culvert or weir) could carry a constant percentage (say 10%) of the incoming flow, then the DI and DQ records could look like the following:

DI	0	100	200	300	400	500
DQ	0	10	20	30	40	50

Since hydraulic structures typically do not function in such linear fashion, it will often be necessary to perform analyses on the diversion structure to develop an inflow vs. diversion flow table.

Once the diversion component is entered into the model, a diversion hydrograph is created based on the unique identifier entered on field 1 of the DT record. This hydrograph can be retrieved at a point later in the model, if needed. An example of such a situation would be where a storm drain take runoff from one watershed and drains it to another. This is accomplished by use of the DR record. This record is simply input into the model at the point where it is needed (preceded by a KK record as with all model components) with the unique identifier from the DT record entered on field 1 of the DR record.

FIGURE 3.12

```
ID EXAMPLE INPUT FILE
ID CAMPBELL BLUE, 3 MILES ABOVE COLEMAN CREEK, AT GAGE STATION
ID 100-YEAR, 3-HOUR MODEL, GREEN AND AMPT (ADOT METHOD)
ID FILE NAME BLUE03.DAT
ID HYDRO-40, 3HR, CENTRAL AZ (0.64 REDUCTION FACTOR)
*
*DIAGRAM
IT     5                    300
IO     5
*
JD  1.80   14.98
PH                 0.75    1.41    2.35    2.67    2.81
*
KK  SA-1
KM CAMPBELL BLUE CREEK SUB-BASIN 1
BA  9.28
LG  0.75    0.25     3.5    0.48       0
UC  2.51    1.45
UA     0       3       5       8      12      20      43      75      90      96
UA   100
*
KK  SA-2
KM CAMPBELL BLUE CREEK SUB-BASIN 2
BA  3.04
LG  0.75    0.25     3.5    0.48       0
UC  1.53    0.87
UA     0       3       5       8      12      20      43      75      90      96
UA   100
*
KK   C-1
KM COMBINE SA-1 AND SA-2
HC     2
*
KK  RC-1
KM ROUTE C-1 TO C-2
RS     5    FLOW      -1
RC  0.06    0.04    0.04   10940  0.0073
RX     0     530     560     620     760     790     810    1200
RY   120      20      10       0       0      10      20     100
*
KK  SA-3
KM CAMPBELL BLUE CREEK SUB-BASIN 3
BA  2.66
LG  0.75    0.25     3.5    0.48       0
UC  1.20    0.67
UA     0       3       5       8      12      20      43      75      90      96
UA   100
*
KK   C-2
KM COMBINE RC-1 AND SA-3 AT GAGE STATION
HC     2
*
ZZ
```

4.0 UNIQUE WATERSHED CONDITIONS

4.1 Transmission Losses

4.1.1 General

Storm runoff and floods in Arizona are usually attenuated through the effects of channel and storage routing, but they are often also diminished due to the percolation of water into the bed, banks, and overbank floodplains of the watercourses. These losses in the watercourses are transmission losses, and these are losses that accrue in the watershed in addition to the rainfall losses on the land surface. Transmission losses can, and often do, result in a significant reduction in the runoff volume. Often, transmission losses only result in a relatively small reduction in flood peak discharge; however, there are situations, such as very long, wide channels with high percolation rates, where the flood peak discharge are dramatically reduced.

The magnitude of transmission loss (both volumetric and peak discharge) is dependent upon the antecedent conditions of the watercourse; characteristics of the bed, bank, and overbank materials; channel geometry (wetted perimeter); depth to bedrock; depth to the ground water table; duration of flow; and hydrograph shape. For a watercourse that is initially dry and is composed of coarse, granular material, the initial percolation rate can be very high; however, the percolation rate diminishes during passage of the flood and would eventually reach a steady-state rate if the flow continues long enough.

Although it is recognized that transmission losses can be an important element in performing rainfall-runoff modeling, particularly for ephemeral watercourses in Arizona, procedures and reliable data for estimating transmission losses are poor. Therefore, except for situations where transmission losses should clearly be incorporated in the analysis (as noted in Procedures Section 4.1.2), the estimation of these losses will not usually be incorporated in rainfall-runoff models.

Two options in the HEC-1 program are available for estimating transmission losses. Both options use the RL record. The recommended option uses an estimated channel percolation rate (PERCRT) and must be used with the channel storage routing option (RS record). The second option estimates the transmission loss as a constant loss (QLOSS), in cfs, plus a ratio (CLOSS) of the remaining flow after subtracting QLOSS. The second method can be used with any of the HEC-1 channel routing options, however, that method is not recommended for general use because of the very subjective decisions that will need to be made in selecting QLOSS and CLOSS. The recommended method is physically-based and should result in better estimates of transmission losses, if adequate estimates can be made of the percolation rate and if the necessary storage routing information can be satisfactorily represented.

4.1.2 Procedure

The following conditions should be met for the consideration of the incorporation of transmission losses into a rainfall-runoff model:

1. The bed, banks, and overbank floodplains of the watercourse are composed of coarse, granular material. Material such as cobble, gravel, sandy gravel, gravelly sand, sand, and sandy loam are all indicators that appreciable transmission losses can occur.

2. There is a relatively long total length of watercourse that is composed of coarse, granular material.

3. The watercourse is ephemeral and it is prudent to assume that the watercourse is dry before the onset of the storm.

4. The bed on the watercourse is not underlain by material, such as bedrock, that would inhibit the sustained percolation of water into the bed of the watercourse.

5. The depth to ground water is great enough to not inhibit the sustained percolation of water into the bed of the watercourse.

If the above conditions are met, then the incorporation of transmission losses into the model should be considered. At this point, two other factors should be considered before proceeding:

1. Incorporation of transmission losses will require a multiple subbasin model with defined routing reaches. Transmission losses will be calculated for the routing reaches. Use of the recommended option for calculating transmission losses will be considered only if a multiple subbasin model is acceptable.

2. Adequate information must be available to provide input for the storage routing method, and the percolation rate can be satisfactorily estimated.

If the above conditions are met, and if it is determined that modeling of transmission losses are vital and practical to the development of a rainfall-runoff model, then proceed to incorporate transmission losses in the model. This will require input of the necessary normal depth storage routing information on RC, RX, and RY records.

The transmission loss will be calculated using information from the RL record (PERCRT and ELVINV). Very little guidance is available for estimating the percolation rates (PERCRT), which can vary from more than 100 inches per hour to less than an inch per hour. Table 4.1 provides some guidance for the percolation rate that can be expected in channels of various bed materials. The elevation of the channel invert (ELVINV) must correspond to the lowest elevation that is used in the 8-point cross section for that routing reach.

Table 4.1
Percolation Rates for Various Channel Bed Materials
(from SCS National Engineering Handbook Section 4, Chapter 19, Transmission Losses, by L.J. Lane)

Bed Material	Transmission Loss Class	Percolation Rate PERCRT Inches/hr
Very clean gravel and large sand	Very High	>5
Clean sand and gravel, field conditions	High	2.0 –5.0
Sand and gravel mixture with low silt-clay content	Moderately High	1.0 – 3.0
Sand and gravel mixture with high silt-clay content	Moderate	0.25 - 1.0
Consolidated bed material; high silt-clay content	Insignificant to Low	0.001 – 0.10

4.2 Wildfire Burn

Wildfires can have an intense impact on a watershed's response to rainfall. Research indicates that soil hydraulic conductivity (infiltration) and moisture deficit (antecedent moisture conditions), as well as reduction in vegetative canopy cover and reduction in watershed resistance coefficients are impacted by the effects of fire. The degree to which the various conditions are impacted is in part, a function of burn severity, vegetation type and density and soil conditions. The resultant hydrologic response is an increase in runoff peak, volume and a more rapid basin response. Note that a burned area will return to pre-fire conditions with time. Research indicates hydrologic recovery to near pre-burn conditions within 3 to 5 years (Schaffner, et al, 2005).

The first step in modeling burned watersheds is an understanding of burn intensity classifications. The US Forest Service Burned Area Emergency Response (BAER) teams estimate burn intensity utilizing remote sensing, verified by intermittent field visits. Site indicators used to evaluate burn severity include soil water repellency, ash depth and color, size of residual fuels and post-fire effective ground cover (USDA Forest Service, 2002). Areas are classified as low, medium/moderate and high intensity burns. The following NRCS guidelines (NRCS, 2000) summarize the classifications:

Low Intensity -

Indicators: Duff and debris partly burned, soil normal color, hydrophobocity low to absent, standing trees may have some brown needles.

Interpretation: Root crowns and surface roots will resprout quickly (with in 1 year); infiltration and erosion potential not significantly changed.

Category type; primarily rangeland; no sediment delivery; natural recovery.

Medium Intensity -

Indicators: Duff consumed, burned needles still evident; ash generally dark colored; hydrophobicity low to medium on surface soil up to 1"deep; soil brown to reddish brown up to 2" of soil darkened from burning (below duff or ash layer); roots viable below 1", shrub stumps and small fuels charred but still present; standing trees blackened but not charcoal.

Interpretations: Root crowns will usually resprout; roots and rhizomes below 1" will resprout; most perennial grasses will resprout; vegetative recovery is rapid (1-5 years); soil erosion potential will increase due to the lack of ground cover and moderate hydrophobocity.

Category type; steep lightly timbered slopes with grass; some sediment delivery.

High Intensity -

Indicators: Duff consumed, uniformly gray or white ash (in severe cases ash is thin and white or light); no shrub stumps or small fuels remain; hydrophobicity medium to high - up to 2" deep; 2-4" of soil is darkened (soil color often reddish orange), roots burned or hard 2 -4'; soil may be physically affected (crusting, crystallization, agglomeration). Standing trees can be charcoal from 0.5 to 1" deep.

Interpretations: Soil productivity is significantly reduced; some roots and rhizomes will resprout, but only those deep in soil; revegetation is set back (5-10 years); soil erosion potential can be significantly increased

Category type; steep timbered north slopes; dense forest canopy; unprotected drainage; sediment delivery; natural recovery severely limited.

Factors contributing to hydrophobic soils include a thick layer of litter; a severe slow-moving surface and crown fire; and coarse textured soils. A simple test to determine if a soil is hydrophobic is to place a drop of water on exposed soil and wait a few minutes. If the water beads up and does not penetrate, the soil is hydrophobic (University of Arizona, 2002).

Note that BAER team burn categories may be grouped together for mapping purposes and burn areas may vary from mapping. Additional field verification may be required to aid the modeler in determination of the dominant burn category.

Depending on the burn-severity, post-fire peak discharge increases may range from 10 to 100 times the pre-fire peak discharges (Neary et al, 2003). In response to a disaster declaration (FEMA-1498-DR-CA) for the October, 2003 California fires, a simple technique to estimate post-burn discharges were developed for the California Regional Regression Equations. Clear water adjustment factors were developed for 100-year peak discharges developed by regional regression equations. The adjustment factors ranged from 1.76 for low-burn conditions to 2.62 for high burn conditions. In addition, sediment bulking adjustment factors, based on basin area, were applied to the adjusted peak discharges. The bulking factors (% increase in peak flow rate) ranged from 40 for 0-3 square miles watersheds, 20 for 3-10 square miles and 10 for above 10 square miles. The post-fire adjustment in 100-year peak discharge is determined by multiplying the pre-burn discharge by the clear water adjustment and the bulking factor. The resulting increase in 100-year peak discharge for a high burn area ranges from approximately 190 to 270% the pre-burn peak discharge, depending on the size of the watershed. The resulting increase in 100-year peak discharge for a low intensity burn area ranges from 90 to 150% the pre-burn peak discharge, depending on the size of the watershed.

A watershed's response to precipitation following a wildfire is also a function of vegetation canopy and cover. An understanding of the change in vegetation canopy and cover due to burn severity will aid in determining the post-fire model parameters. Table 4.2 illustrates the modification in vegetation canopy and covers for different vegetation types and burn intensity. Recent research (Stone, 2006) indicates that grasslands rarely exhibit a high intensity burn.

4.2.1 Rainfall Losses

Table 4.3 provides guidance for the modification of Green and Ampt rainfall loss parameters to account for burn severity. Prior to adjusting the rainfall loss parameters, the dominant burn severity should be determined for the subwatershed under investigation. Surface retention is reduced by moderate and high severity wildfire, and the reduction in vegetative cover and hydrophobicty and surface sealing reduce the hydraulic conductivity of soils, changing XKSAT. Please note that DTHETA is a measure of the soil's capacity to store rainfall. Assuming that the soil moisture is dry, will result in a decrease in rainfall losses. Therefore it is recommended that DTHETA be left at the pre-burn value.

Table 4.2 Cover values are a function of pre-burn cover properties for different vegetation types modified by burn intensity. Ground cover includes pebbles.

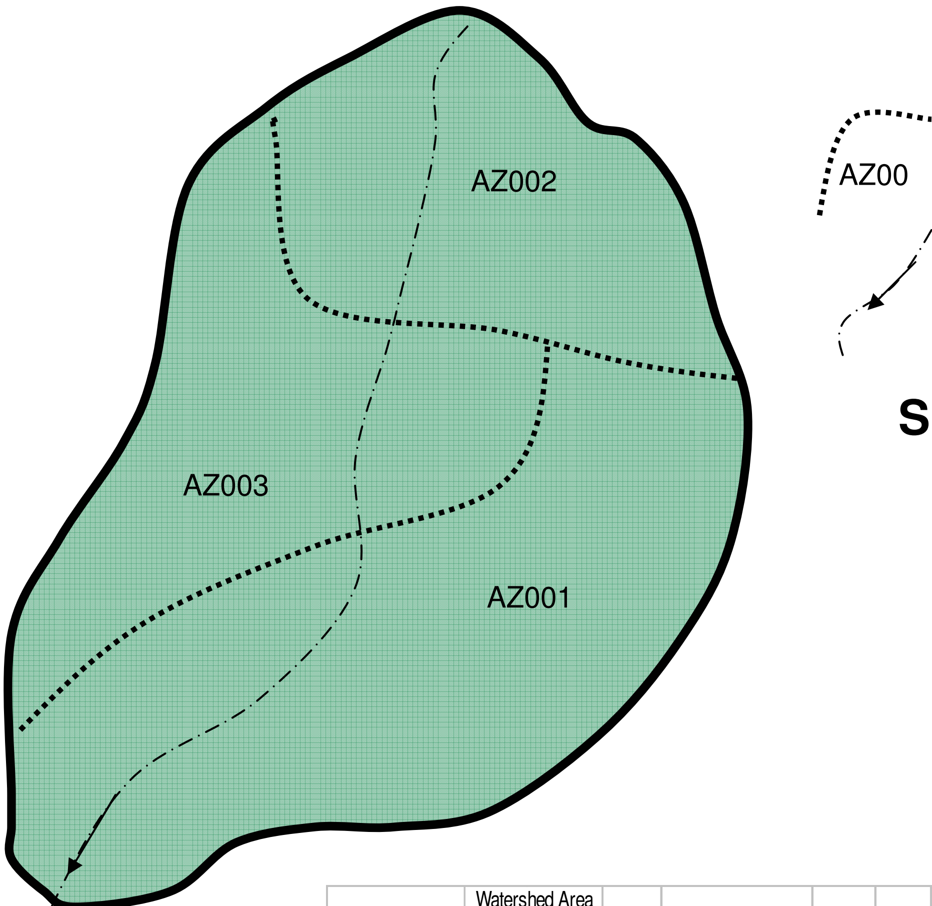
(Source: C. J. Wilson Et al, 2001)

Cover Type	Canopy Cover (%)	Ground Cover (%)
Developed	10	90
Grassland	90	90
Ponderosa pine	80	90
Mixed conifer	80	90
Aspen	80	90
Pinon/juniper	35	80
Water/shadows	80	90
Bare ground	5	50
Juniper woodland	20	70
Low burn developed	9	73
Low burn grassland	77	73
Low burn ponderosa pine	68	73
Low burn mixed conifer	68	73
Low burn aspen	68	73
Low burn pinon/juniper	30	65
Low burn water/shadows	68	73
Low burn bare ground	4	43
Low burn juniper woodland	17	58
Moderate burn developed	4	55
Moderate burn grassland	38	55
Moderate burn ponderosa pine	34	55
Moderate burn mixed conifer	34	55
Moderate burn aspen	34	55
Moderate burn pinon/juniper	15	50
Moderate burn water/shadows	34	55
Moderate burn bare ground	2	35
Moderate burn juniper woodland	9	45
High burn developed	0	24
High burn grassland	2	24
High burn ponderosa pine	2	24
High burn mixed conifer	2	24
High burn aspen	2	24
High burn pinon/juniper	1	23
High burn water/shadows	2	24
High burn bare ground	0	22
High burn juniper woodland	0	23

Table 4.3 Green and Ampt Rainfall Loss Parameters Guidance for Burned Areas

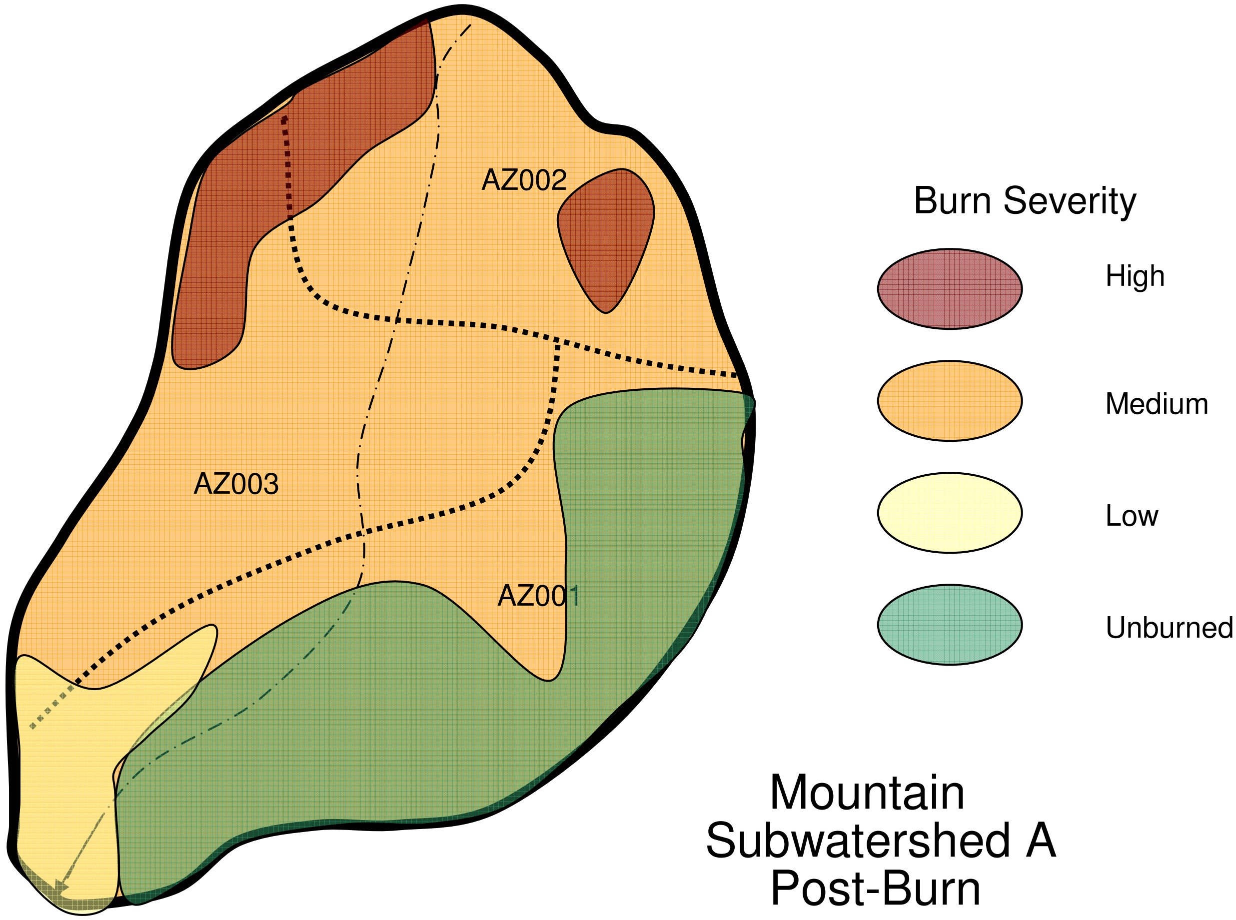
Burn Severity	Rainfall Loss Parameters				
	IA	DTHETA	XKSAT	PSIF	RTIMP
Low	no significant change in surface retention	no change in soil moisture deficit	reduction in correction factor for vegetative cover	determined based on XKSAT	no change in effective impervious cover area
Moderate	reduction in surface retention	no change in soil moisture deficit	assume bare ground no correction factor for vegetative cover	determined based on XKSAT	no change in effective impervious cover area
High	no surface retention	no change in soil moisture deficit	no correction factor for vegetative cover reduce to reflect hydrophobicity and surface sealing	determined based on XKSAT	no change in effective impervious cover area

The following example illustrates the use of the guidance. Subwatershed A is comprised of three soil groups with 40% cover and burns under a range of severities. The dominant burn severity is assumed medium. Based upon the above guidance no correction factor is applied for vegetative cover in comparison to a 1.3 correction for pre-burn conditions. Surface retention loss is reduced to 0.15.



Mountain
Subwatershed A
Pre-Burn

	Watershed Area												
	(acres)	(sq miles)	Soil	Texture	Area (acres)	%/100	XKSAT	Composite XKSAT	DTHETA	PSIF	Adjusted XKSAT	Impervious (%)	Initial Loss (inches)
Sub Watershed A	260	0.41	AZ001	gravelly fine sandy loam	126	0.48	0.4						
			AZ002	loam	59	0.23	0.25						
			AZ003	loam	75	0.29	0.25						
					260	1		0.31	0.25	4.6	0.41	0	0.25



Mountain Subwatershed A Post-Burn

	Watershed Area (acres)	(sq miles)	Soil	Texture	Area (acres)	%/100	Burn Severity	XKSAT	Composite XKSAT	DTHETA	PSIF	Adjusted XKSAT	Impervious (%)	Initial Loss (inches)
Sub Watershed A	260	0.41	AZ001	gravelly fine sandy loam	126	0.48	Medium	0.4						
			AZ002	loam	59	0.23	Medium	0.25						
			AZ003	loam	75	0.29	Medium	0.25						
					260	1.00			0.31	0.25	4.6	0.31	0	0.15

4.3 Grazing

Livestock grazing activities can alter the landscape surface and soil characteristics that influence rainfall-runoff magnitudes. Without proper management, over grazing can result in soil compaction and loss of topsoil due to wind and/or water erosion.

From a hydrologic modeling perspective, loss of the surface soil layer can change the infiltration characteristics or result in a different soil horizon that controls the infiltration rate. Soil compaction has been found, under certain soil conditions, to extend down to depths of approximately 4 inches (Mulholland and Fullen, 1991). The net result of over grazing activities is a decrease in infiltration rates by as much as 35% (Fiedler et al, 2002).

When modeling areas that are or suspected to be impacted by over grazing, it is strongly recommended that the local NRCS office or Forest Service office be contacted. In many areas, the NRCS is responsible for range management and/or has information on the extent grazing activities over time. Depending on climate and rainfall, the impacts of grazing can last for many years after grazing activities have ended (Neff et al, 2005). The effects of over grazing activities on soil characteristics may already be accounted for in current soil surveys for the area. In addition, the NRCS may have prepared special reports documenting the conditions that could be useful from a modeling perspective.

Modifications to hydrologic parameters are not required for well-managed grazing areas. A reduction in the correction factor for vegetative cover based on field reconnaissance should be considered for heavily or over-grazed areas.

4.4 Logging

The impacts of logging on hydrologic processes are dependent on the magnitude of the logging and the recovery time period. In addition, logging roads can change concentration points and create diversions. Logged areas which dominate a subwatershed should be adjusted for vegetative cover, similar to low burn severity areas.

Depending on the duration of the recovery period, surface erosion due to loss of vegetative cover can alter the infiltration characteristics as discussed in Section 4.3. Similar to grazing, it is strongly recommended that the local U. S. National Forest office (or other applicable federal agencies) be contacted for any site specific information on logging activities or special studies that may be useful in estimating hydrologic parameters.

4.5 Drought

Drought is a normal, recurrent feature of climate and natural processes. Drought, as it relates to hydrologic modeling, can alter the physical processes that control rainfall losses. As drought is a recurrent natural condition, the effects on soil and vegetative conditions is most likely already accounted for in available data sets (particularly soil surveys) used to estimate hydrologic parameters. However, many areas of the State have been recently subjected to sustained and in certain locations severe drought conditions. Given the age of many of the available soil surveys, it is possible that soil and vegetative characteristics have changed.

Soil characteristics that are impacted by drought are primarily related to soil moisture. As soil moisture is reduced, soil biota and vegetation becomes dormant or eventually dies entirely.

Loss of soil biota and vegetation leads to surface erosion, which in turn can alter the infiltration rate as discussed in Section 4.3. Additionally, reduction in soil moisture allows for the formation of cemented layers, which can reduce the infiltration rate. If it is felt that drought has potentially altered the soil conditions from the available information it is strongly recommended that the local NRCS office be contacted.

4.6 Rapid Snowmelt

4.6.1 Background

Runoff from snowmelt is, most often, a relatively slow process that, according to the Federal Emergency Management Agency (FEMA) is equivalent to a light to moderate rainfall. Yet, certain areas of the country (Northeast and North Central portions along with some areas of the Western U.S.) are particularly susceptible to snowmelt flooding. In Arizona runoff from snowmelt alone is not generally a major source of flooding. However, it has been observed that rainfall in addition to snowmelt has produced some exceptionally large runoff events, such as the widespread floods of January – February 1993. Areas in Arizona that may be particularly susceptible to rain-on-snow runoff events are the mid elevation zones (around 7,000 feet) such as the Mogollon Rim and the mountain islands of the southern/southeastern portions of the state (Gottfried et al., 2002).

Runoff from snowmelt is a very complex process that occurs when the snow becomes isothermal at 32 °F and its liquid water holding capacity has been reached (USACE, 1998). The snowpack in this condition is often referred to as ripe. This condition is important because very little energy is required to initiate melting (Harr, 1981). Sources of energy that initiate the snowmelt process are:

- Shortwave radiation
- Long-wave radiation
- Convection from the air (sensible energy)
- Vapor condensation (latent energy)
- Conduction from the ground
- Energy contained in rainfall

The degree to which each form of energy drives the process is a function of numerous environmental, topographic and meteorological factors such as:

- Canopy cover
- Cloud cover
- Aspect and slope of terrain
- Latitude of site
- Season
- Time of day
- Reflectivity of the snow (albedo)
- Wind direction and speed
- Temperature

For rain free conditions, shortwave radiation is the most significant source of energy input. For rain-on-snow conditions turbulent exchange (sensible and latent energy) is the most significant form of energy input. The principle factors affecting sensible energy are the temperature gradient and the corresponding wind speed (USACE, 1998; Marks et al, 1998).

4.6.2 Methodologies

There are several methods, equations and tools available for estimating runoff from snowmelt. Two of the most common are the Degree-Day and Energy-Budget Methods. Both of those are coded in HEC-1 and can be coupled with rainfall-runoff.

The Degree-Day Method is a relatively simple model of the snowmelt processes that is often referred to as the Temperature Index Method. The Degree-Day Method relies on temperature as an index to the energy budget. It is implemented in HEC-1 with the following data inputs.

- Elevation zone data
    - Drainage area
    - Snow-water equivalent
    - Normal annual precipitation
- Melt coefficient data
    - Temperature lapse rate
    - Snowmelt coefficient
    - Index temperature at which snow will melt
- Temperature time series data

The Energy-Budget Method considers the major sources of energy input and is a more sophisticated and accurate model of the snowmelt processes. It is implemented in HEC-1 with the three input data sets listed for the Degree-Day Method plus the following:

- Shortwave radiation time series data
- Dew point time series data
- Wind speed time series

Use of one method over another is ideally a function of the intended application and required output. Table 4.4 summarizes generally accepted approaches for modeling several typical applications for rainfall/snowmelt runoff conditions. Other factors that must also be considered in the method selection are data availability and degree to which snow is a factor (USACE, 1998). While the Energy-Budget Method provides a more accurate representation of the snowmelt processes, Table 4.4 indicates that either method is generally acceptable for most rain-on-snow applications. Use of the Energy-Budget Method is also restricted in practice due to data availability limitations. Therefore, for this State Standard, the recommended method for estimating snowmelt is the Degree-Day Method.

Table 4.4
Snowmelt Method Considerations

Application	Example	Melt Calculation: Snow Conditioning	Melt Calculation: Degree-Day	Melt Calculation: Energy-Budget
Single event: rain-on-snow	Hypothetical floods in coastal mountains	Assume Ripe	Possibly	Possibly
Single event: snow (plus rain)	Hypothetical floods in interior basins	Assume Ripe	Yes	Yes
Single event forecasting: rain-on-snow	Short-term flood forecasting	Optional	Yes	No
Single event forecasting: snow (plus rain)	Short-term flood forecasting	Optional	Yes	No
Continuous simulation	Long-term flood and drought forecasting	Required	Yes	Possibly
Detailed simulation on small watersheds	Research and Development	Required	No	Yes

Source: adapted from Table 10-1 EM 1110-2-1406 Runoff from Snowmelt (USACE, 1998)

4.6.3 Guidelines

Modeling of rain-on-snow events requires the characterization of both rainfall-runoff and snowmelt-runoff conditions. Characterization of the rainfall-runoff conditions for a rain-on-snow event is essentially the same as discussed in previous sections with a few minor modifications/considerations. Information and guidelines for modeling snowmelt conditions and rainfall-runoff conditions are provided in the following sections.

<u>Snowmelt-Runoff</u>

The Degree-Day Method as implemented in HEC-1 is described by the following equation:

$$M_s = C_m (T_a - T_b)$$

where

M_s = *snowmelt, in inches/period*
C_m = *melt rate coefficient, in inches/(degree/period)*
T_a = *air temperature lapsed to the midpoint of the elevation zone, in °F*
T_b = *base temperature at which snow melts, in °F*

Information and guidance for the selection/determination of each variable are provided in the following sections.

Snowmelt Coefficient

The key variable in the snowmelt equation is the melt rate coefficient, C_m. The magnitude of C_m is a function of albedo, canopy cover, cloud cover, rainfall and wind. For rain-free conditions, C_m typically ranges from 0.04 to 0.08 inches/°F (USACE, 1998). For rain-on-snow conditions, values of C_m can range from 0.06 to 0.20 inches/°F (USACE, 1994). In general, the magnitude of C_m tends to increase with increases in wind velocity (Marks et al, 1998) and to a lesser extent with increases in rainfall and humidity.

The magnitude of C_m is also relative to the basis of the temperature index and can vary with time. This is typically only a consideration for long-duration simulations where temperature index data is on the order of days and the basis of input is the maximum or minimum daily temperature.

Base Temperature

The base temperature is the temperature at which snow melts and precipitation falls as either rain or snow. For most applications and locations, the base temperature is at or near 32 °F (USACE, 1998). At temperatures greater than 2 °F plus the base temperature, precipitation is treated as rain.

Similar to the snowmelt coefficient, the base temperature is relative to the temperature index. For example, if the temperature index is based on the maximum daily temperatures, the base temperature is higher, possibly as high as 40 °F (USACE, 1998). This, again, is generally only a concern for long-duration simulations.

Air Temperature

Air temperature (temperature index) is a highly variable parameter that cannot readily be generalized. This is complicated by the fact that the areas within the State that are susceptible to snowmelt, limited data is available. Sources of temperature data are listed in Table 4.5. The source(s) that provides the most appropriate data depends on the specific application. For long-duration simulations, daily data (mean, maximum and minimum) temperature may be sufficient. For short-duration simulation/hypothetical simulations, hourly data is preferred. If hourly data is unavailable, a synthetic data set can be generalized using local mean, maximum and minimum data temporally distributed according to a representative pattern (e.g. trapezoidal) or mimicking the distribution from an adjacent/meteorologically similar location.

Table 4.5
Temperature Data Sources

Source	Internet Address	Data Type
Western Regional Climate Center	http://www.wrcc.dri.edu/summary/Climsmaz.html	Daily
NRCS SNOTEL	http://www.wcc.nrcs.usda.gov/snow/	Daily
National Weather Service	http://www7.ncdc.noaa.gov/IPS/getcoopstates.html	Daily
Arizona Meteorological Network	http://ag.arizona.edu/azmet/azdata.htm	Hourly

Each of these data sources maintains temperature (and other climate data) extending back several years (often 30 or more). This data should be inspected to identify representative conditions, particularly in regard to known rain-on-snow events. Generally this can be limited to the months of January, February and March.

If more than one temperature station is located within the watershed/region, then the data should be inspected in regard to the establishment of a site-specific temperature lapse rate. Temperature lapse rate is the rate at which temperature changes with elevation. Lapse rate varies with time of day and season (Harlow et al, 2004). Typical values for lapse rate range from –3 to –5 °F per 1,000 feet of elevation gain. In a study specific to southeastern Arizona, lapse rates for January, February and March are estimated for mean, maximum and minimum air temperatures. Those values are listed in Table 4.6.

Table 4.6
Temperature Lapse Rate for Southeastern Arizona

Temperature	**Lapse Rate °F/1,000 ft**
Mean	-1.65 to -3.84
Maximum	-2.19 to -4.11
Minimum	-0.55 to -2.19

Source: Derivation of temperature lapse rates in semi-arid south-eastern Arizona (Harlow et. al., 2004))

Snow Water Equivalent

Snow water equivalent, SWE, is the depth of water that results from melting a given depth of snow and it is a function of both the depth and density of the snow (NRCS, 1997). In other words, SWE is the volume of water stored in the snow pack that is available for runoff. Estimates of SWE are determined by the NRCS at each of the SNOTEL stations. SNOTEL data can be viewed and downloaded from the link listed in Table 4.5.

In lieu of site-specific SWE data, estimates of SWE can be made using snow depth and density. Snow depth data is collected at numerous sites throughout Arizona and published on the Arizona Meteorological Network website (address listed in Table 4.5). One limiting factor with this approach is that snow density varies with depth in the snow pack and time. In the mountainous areas of California, the typical snow density is 12 percent. However, late in the snow season (after May) snow density is typically above 50 percent (California Department of Water Resources). Similar results can be expected in Arizona.

Snowmelt Losses

As snow melts, the volume of water released may be subjected to the same loss conditions as rainfall on the watershed. In HEC-1, when the snowmelt routines are invoked only the HEC Exponential Loss Rate or Initial and Uniform Loss Rate Methods can be used (for both rainfall and snowmelt). Of these, the Initial and Uniform Loss Rate Method is recommended for this State Standard for the rainfall component.

The Initial and Uniform Loss Rate Method can be a convenient substitute for the Green and Ampt infiltration equation for rain-on-snow conditions if an assumption is made that the watershed is saturated. Under saturated conditions, DTHETA of the Green and Ampt infiltration equation is zero and the magnitude of the losses during the decay of the infiltration capacity from normal antecedent conditions to a steady state condition approaches zero. Thus, for saturated conditions the Initial and Uniform Loss Rate method is the steady state form of the Green and Ampt infiltration equation. In the Initial and Uniform Loss Rate Method, the uniform loss rate is the same as XKSAT of the Green and Ampt infiltration equation. The initial loss is the same as the surface retention of the Green and Ampt infiltration equation with the addition of infiltration prior to the steady state condition. The additional losses can be easily approximated using the results of the model with the Green and Ampt infiltration equation parameters.

For the snowmelt component, losses (if appropriate) can only be modeled using the HEC Exponential Snowmelt Loss Rate Method. For this method, there is not an initial loss only a loss rate. The loss rate can either be uniform or decay based on some rate of change. For most purposes, assuming a uniform loss rate is sufficient.

Rainfall-Runoff

The rainfall-runoff model parameters for a rain-on-snow event are essentially the same as discussed in Section 3, with the exceptions that rainfall may fall as snow and the temporal issues associated with the movement of water through snow. The movement of water through snow is more complex than the infiltration of water into soil due to the continuously changing conditions of the snow pack during the rainfall/snowmelt event (USACE, 1998). In addition, the routing processes are complicated by the influence of environmental factors such as canopy cover. For example, in the shallow snow packs of British Columbia the difference in time to peak runoff between forest and open sites can be several hours (Kattelmann, 1987). Another factor influencing the time delay is the watershed slope. For steep, mountainous watersheds, the time delay may be minimal (USACE, 1998). Because of the complexity of the process adjustments to unit hydrograph parameters for movement of water through snow are not recommended unless approved by the appropriate jurisdictional agency.

4.6.4. Procedures

Starting with the basic input for a rainfall-runoff model for the watershed add/change the following:

1. Change the Green and Ampt infiltration equation rainfall loss parameters to the Initial and Uniform Loss infiltration parameters. Uniform loss is the same as XKSAT in the Green and Ampt infiltration equation. Estimate the initial loss from the results of the base model with the Green and Ampt infiltration equation such that the total losses are equivalent.
2. Elevation zone data – elevation zone data characterizes the effects that topographic relief play in the physical characteristics of snowmelt and the point at which precipitation is either snowfall or rainfall. In HEC-1 up to 10 elevation zones can be used to characterize the topographic relief of the drainage area. Elevation zones must be in equal intervals (e.g. 1,000-foot intervals) and correspond to the temperature lapse rate. The drainage area is the incremental area associated with each elevation zone.
    a. Determine the drainage area associated with each elevation zone, in square miles
    b. Determine the SWE associated with each elevation zone, in inches,
    c. Optional; input the annual precipitation associated with each elevation zone, in inches
3. Melt coefficient data

a. Select the temperature lapse rate associated with the elevation zone interval, in degrees Fahrenheit. For southeastern Arizona, select a value from Table 3. For other areas, estimate from available data or use a value between –3 and –5 °F/1000 feet.
b. Select a melt rate coefficient associated with the appropriate basis of the temperature index. For non-forested areas with windy conditions select a value toward the upper end of the range of 0.06 to 0.2 inches/°F.
c. Select a base temperature. Typical values for base temperature are 32 to 34 °F.

Temperature index data – input temperature series data for the entire simulation period. The starting time is assumed to be the same starting time as the rainfall.

An example of the procedure is provided in the Technical Supplement.

4.6.5 Applications and Limitations

While it is recognized that rain-on-snow events occur, application of rain-on-snow as a general design condition is not recommended. Situations for which rain-on-snow investigations are appropriate include flood warning, flood preparedness planning and emergency access analyses.

Rain-on-snow analyses require considerable judgment particularly when sufficient data is limited, as is the case for most of Arizona. It is therefore recommended that a rain-on-snow analysis include sensitivity tests of the input parameters. The number of sensitivity tests that may be required is a function of the quality of site-specific data.

4.7 Urbanization

Time of concentration formulas and time-area curves for urban areas should be utilized when modeling urban watershed. In addition, kinematic wave channel routing is recommended for runoff translation.

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